U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-292 995

Commuter Exposure Modeling Methodologies

SRI International, Menlo Park, CA

Prepared for

Environmental Sciences Research Lab, Research Triangle Park, NC

Feb 79

United States
Environmental Protection
Agency

Environmental Sciences Research
Laboratory
Research Triangle Park NC 27711

EPA-600/4-79-010
February 1979

Research and Development

PB 292995

EPA

Commuter Exposure Modeling Methodologies

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TECHNICAL REPORT DATA
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1. REPORT NO. EPA-600/4-79-010	2.	3. RECIPIENT'S ACCESSION NO. PB292995
4. TITLE AND SUBTITLE COMMUTER EXPOSURE MODELING METHODOLOGIES		5. REPORT DATE February 1979
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Patricia B. Simmon and Robert M. Patterson		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS SRI International 333 Ravenswood Avenue Menlo Park, California 94025		10. PROGRAM ELEMENT NO. 1AA601 CA-04 (1977)
		11. CONTRACT/GRANT NO. 68-02-2754
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory - RTP, NC Office of Research and Development U. S. Environmental Protection Agency Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final 9/77 - 10/78
		14. SPONSORING AGENCY CODE EPA/600/09

15. SUPPLEMENTARY NOTES

16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
* Air pollution * Vehicular traffic * Personnel * Exposure * Mathematical Models		13B 05I 06T 12A

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 168
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE A08- A01

EPA Form 2220-1 (9-73)

EPA-600/4-79-010
February 1979

COMMUTER EXPOSURE MODELING METHODOLOGIES

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ABSTRACT

Two methodologies for modeling commuter exposures are proposed: computer-oriented approach and a manual approach. Both modeling methodologies require that major commuter routes, or pathways, be identified and that the traffic on the remainder of the roadway network be treated as background pollutant sources. Since the majority of pathway exposure is expected to result from emissions on the pathway itself, the emissions and dispersion of non-pathway source pollutant are handled in a simple fashion. Pathway traffic undergoes a more sophisticated treatment, in that congestion and delay due to signalization are accounted for and emissions are computed accordingly. The methodology used to simulate the dispersion of pathway emissions utilizes three separate dispersion treatments, according to whether the roadway is limited-access, non-limited access, or a street canyon.

The numerical and manual models will each consist of three distinct modules that treat traffic, emissions, and dispersion. The numerical model is designed to compute exposures on a network of pathways for either a short-term, worst-case commute or for the commutes during an average year. Annual or short-term commuter exposure statistics will be produced by the numerical model. The manual methodology relies on a number of graphs and nomograms to produce exposures for a single commute on one or more commuter routes. The input data requirements of each modeling methodology is discussed. The data required for model evaluation and the availability of data bases both for model input and for evaluation purposes are also discussed. A critical evaluation of the modeling approaches is also presented, including discussions of development costs, model deficiencies, and model accuracies.

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I INTRODUCTION

Commuters are exposed to pollutants at levels high enough to cause widespread concern, and this concern has been heightened by studies indicating that commuters are exposed to more roadway-generated pollutants than any other group. The results of preliminary studies of the commuter exposure problem are recognized as first order approximations. To more accurately assess the exposures to which commuters are subjected, the areawide concentration patterns that occur during commute hours must be determined. Such patterns depend on factors such as meteorological conditions, traffic volume distributions in space and time, roadway characteristics, distributions of vehicle types and models, vehicle operating characteristics, intersection signalization, and vehicle emissions. These factors must therefore play an important role in a model that can simulate commuter emission patterns and the subsequent action of the atmosphere in dispersing the emissions.

This report proposes the elements of a commuter exposure model. Two approaches have been formulated to predict pollutant concentration patterns arising from vehicular sources: (1) an approach involving numerical techniques, and (2) an approach involving simple charts and nomograms. The manual approach is a simplified version or subset of the numerical approach.

The basic modeling methodology is comprised of four parts, each of which is concerned with one aspect of commuter exposure modeling. The first part of the methodology--the definition of the modeling area--will be executed by and requires the judgement of the user. The remainder of the methodology--treating traffic, emissions, and dispersion--will be executed on a computer (in the case of the numerical model) or by the user with the aid of worksheets, tables, and nomograms (in the case of the manual model). The methodologies recommended for defining the modeling area and simulating traffic, emissions, and dispersion are described in detail for the numerical model in Section II and for the manual model in Section III. The formulations presented could apply to almost any inert pollutant, but it was assumed, as the general commuter modeling methodology was being developed, that carbon monoxide was the pollutant of primary concern.

Because of the flexibility gained through the use of a high-speed computer, the numerical methodology will allow computation of both annual average and short-term, worst-case commuter exposure statistics. The manner in which the statistics are developed is discussed in Section II, and a presentation of the types of output available with each modeling approach appears in the sections of this report that deal with the numerical and manual methodologies.

The content of Section IV concerns the specification of data. The data input requirements of the two modeling approaches are given, and the data needed to evaluate the models are discussed. The availability of existing data bases is also examined.

The final section of this report contains an evaluation of the two modeling approaches. Items such as development costs, both in dollars and time, and the deficiencies and accuracies of the model are investigated.

II NUMERICAL COMMUTER EXPOSURE MODEL

A. General

The basic numerical commuter exposure modeling methodology is separated into three distinct parts that consider traffic flow, emissions, and atmospheric dispersion. When the code for the model is written, separate modules treating each of these topics should be maintained, to facilitate model updates necessitated by improved technology. The modeling approaches are defined in Subsection II-B. The techniques to be used to compute the parameters relating traffic, emissions, and dispersion are described in Subsection II-C through II-E. Subsection II-F contains a detailed discussion of the output of the numerical model and how it will be formulated from model computed statistics, while Subsection II-G is a summary of the numerical methodology as a whole. In this subsection, a more general discussion of model ouput, and its effect on the design of the methodology itself, is presented.

Naturally, the information desired by the model user plays a key role in the design of any model. Basically, two types of statistics are of interest to the commuter exposure modeler: (1) so-called short-term statistics, concerning a single commute during worst-case meteorology: and (2) annual statistics, which describe average exposure or the frequency of occurrence of exposure throughout a year. The numerical model methodology is designed so that it may produce either type of statistic.

In both the annual and short-term modes, the model allows the user to compute exposures for the "average" commuter on each of the pathways. (The "average" commuter is the driver who commutes mostly during the peak travel period.)

The differences in the way the model will compute annual and short-term exposures concern the consideration of the time period of the commute. Annual statistics require computations for each of various meteorological and traffic condition combinations, so it is assumed that the meteorology and the traffic volumes on the pathways do not change during the commute period. That assumption reduces the number and complexity of the required computations, because it eliminates the need to contend with time sequences of meteorology and traffic during the commute period. The annual exposure statistics developed under the methodology will be "average," in the sense that the traffic and meteorological conditions used in the computations are the average prevailing conditions during a commute.

For an in-depth, worst-case analysis, the model should be used in the short-term mode, in which both traffic and meteorology will be allowed to vary with time. If the average commute on a pathway lasts longer than one hour, the traffic volumes and meteorological conditions may change for the next hour.

B. Defininition of the Modeling Approaches

The crux of the commuter exposure modeling problem is defining the modeling area. Ideally, the definition of the modeling area should be the same for the numerical and graphic models. As a minimum, the definition for the graphic model should be a subset of that for the numerical model. The modeling area should coincide with the Standard Metropolitan Statistical Area (SMSA) or the Air Quality Control Region (AQCR) bounding the urban core. Such a practical choice has been made because those areas usually encompass the region that influences and is impacted by the urban core, and because a wealth of requisite data is routinely available for them. Generally, the SMSA and AQCR boundaries are the same.

This section describes a methodology for defining the modeling area in terms of the two important types of emission sources in a commuter exposure model: (1) line sources, or commuter pathways; and (2) non-pathway sources (the "background source effects") from the remaining roadway network.

1. Commuter Pathways

The most critical aspect in defining the modeling area is choosing the appropriate commuter pathways. The commuter exposures that are calculated and the statistics that are derived all depend directly on the pathways that are defined.

Fortunately, the major commuting pathways, or "commuting corridors," are well-defined and recognizable if one is familiar with the modeling area. Often, just the physical size of the roadway, or, more properly, its capacity, will identify it as a commute route. The commuting pathways are also corridors of development, fostered largely by the access to the urban core that the route provides.

From a methodological standpoint, however, it is suggested that the user of the commuter exposure models seek advice in defining the major commuting routes. The local transportation department, the metropolitan transportation planning authority, or the council of governments should be able to provide this assistance. The remainder of this discussion provides the criteria that should be presented to the transportation expert to help him help the model user in defining the commuting pathways.

a. Origin-Destination Zones

A key part of the transportation planning process is the estimation of trends of demand for transportation services. Estimates of demand are based on a knowledge of existing demand, and on known and planned land-use and demographic characteristics of the planning region. Tools that help quantify this demand are the origin-destination survey and the additional data that can be generated from the survey results.

Typically, the region is divided into subareas, or zones. They are of variable size, depending on population density and other demographic characteristics, and on the roadway network. The zones are smaller and denser in the urban core than in outlying areas. For example, the transportation planning region for Pittsburgh encompasses about 9000 square miles and contains approximately 900 zones. However, about 100 of them are in the downtown, "Golden Triangle," area of the city.

In simplest form, the origin-destination data will supply the daily trips between zones. Thus, they may be broken down by trip purpose, by trip purpose pairs indicating the direction of flow (home-work, work-home), and by time of day. For the commuter exposure model, trips to and from work are the main ones of concern in defining the commuting routes. Fortunately, work trips have the most tractable statistics. They are likely to vary the least from one weekday to the next and they occur during fairly well-defined time periods. They are relatively insensitive to weather and travel conditions. Additionally, even if the trip is identified only as a work trip, it can be assumed to be from home to work in the morning and from work to home in the evening. The origin-destination data are usually presented as a matrix, with an accompanying map indicating the zones. The matrix elements are the numbers of trips between origins and destinations.

The purpose of origin-destination data for commuter exposure modeling is to define the commute pathways. Accepted accuracy for the data is ± 20 percent, so they should not be used to generate traffic volumes. Their utility lies in showing the spatial flow of home-work and work-home trips. Once the spatial flow is known, the key roadways can be determined, and traffic volumes can be taken from volume flow maps.

Given fairly comprehensive origin-destination data, it would be tempting to try to model all commuters. All of the work-related trips are identified, and one could seemingly define routes for them and model the exposures. But the futility of doing so becomes readily apparent when the Pittsburgh example is considered: the toal number of possible origin-destination pairs is 900^2, or 810,000. Even as few as 100 zones would yield 10,000 combinations. While not every combination will produce a work-related trip, the percentage is large enough to render such an approach impractical.

b. Definition of Commute Pathways

For commuter exposure modeling to be a manageable problem, a reasonable number of major commuting routes or pathways must be defined even though a plethora of origin-destination data is available. The number of pathways will be a function of the size of the modeling area, but it should be about 25 or less. Those routes will generally have the highest number of vehicle miles traveled (VMT) by commuters. Again it is recommended that the advice of a transportation planner or traffic engineer familiar with the area be sought when the routes are defined.

It is recognized that the commute pathways defined in such a manner will not carry all commuters. However, the method described here should include a great majority of the commuters who are at risk of experiencing high exposures on the order of the air quality standards. Most of the extensive commuting will be done along the defined pathways, both in time and distance, and the pathways will by definition carry high volumes of traffic. Although their total number may be close to that on the pathways, the commuters "missed" will, on the average, be traveling shorter times and distances on less heavily traveled roads. They are not considered to be at risk to high pollutant exposures during their commute.

Commuting trips do not begin on the commute pathways as defined here, but rather, on local surface streets and "collectors." Often, they will not even begin in the same zone that they are in when they enter the pathway. To handle the exposure during the approach to and departure from the pathway, minor pathways should be used that are representative of the travel to and from the route.

c. Characteristics of Pathway Sections

Two types of roadways are candidates for commute pathways: expressways and arterials. A pathway may be composed of both. The Highway Capacity Manual[1] (HCM) defines an expressway as "a divided arterial highway for through traffic with full or partial control of access and generally with grade separations at major intersections." (A freeway is defined as an expressway "with full control of access.") The term arterial is intended to have the meaning that the HCM applies to a major street or highway: "an arterial highway with intersections at grade and direct access to abutting property, and on which geometric design and traffic control measures are used to expedite the safe movement of through traffic."

The other descriptors that characterize the pathways pertain to physical location and include street canyons and cut, fill, elevated, and at-grade sections. For on-roadway concentration calculation, the second group may be taken together. That is discussed later in this section.

2. Non-Pathway Sources

a. Definition of Grid System

Non-commute pathway pollutant emissions will be treated on a grid square basis. The modeler will overlay the study area with a grid system, and the grid squares will have dimensions of 2 km by 2 km.

The coordinate system used to define the grid must be consistent with the system used to define commuter pathway coordinates. Grid squares will be defined by their lower left corner coordinates, and the input data required can be abbreviated for sections of the study area in which grid square descriptors have the same value.

The grid square coordinates, and other grid square descriptors described in the next two sections, need be input to the model for only those squares through which commuter pathways pass. Figure 1 illustrates a typical commuter pathway network, overlaid by a grid system. The shaded grid squares are those for which input data are required.

b. Apportionment of Vehicle Miles Traveled on the Primary Network

The primary street network is defined as those roadways carrying a major amount of the total vehicle miles traveled (VMT) on the entire roadway network of a metropolitan area. In general, the primary network can be considered to be those streets for which average daily traffic (ADT) values are available. For the commuter exposure model, the primary network will not include roadways that are commuter pathways.

Because the major part of the concentration on a commuter pathway is expected to result from vehicles traveling on the pathway itself, the part of the concentration resulting from the other non-pathway roadways in the vicinity can be approximated. The approximation to be used in the model will consist of an aggregation of primary network emissions into grid squares, with the assumption of a uniform emission rate across the square. This approach will save the user the considerable effort that would be required if each roadway in the primary network, and its associated characteristics, were used as model input.

Therefore, once the grid system is defined, the user must apportion the total VMT of primary network streets among the grid squares and input that information for the appropriate squares. The recommended approach for the apportionment is the following. A volume flow map showing the ADT on the major roadways in the study area should be overlaid with the grid system. The length of the portion of each roadway that lies in the grid square should be multiplied by the number of vehicles traveling on that roadway each day, yielding the VMT on the portion of the roadway that lies in the grid square. This procedure should be followed for each portion of roadway in the grid square; the total VMT in the grid square will be the sum of the individual roadway VMTs. The measurement of

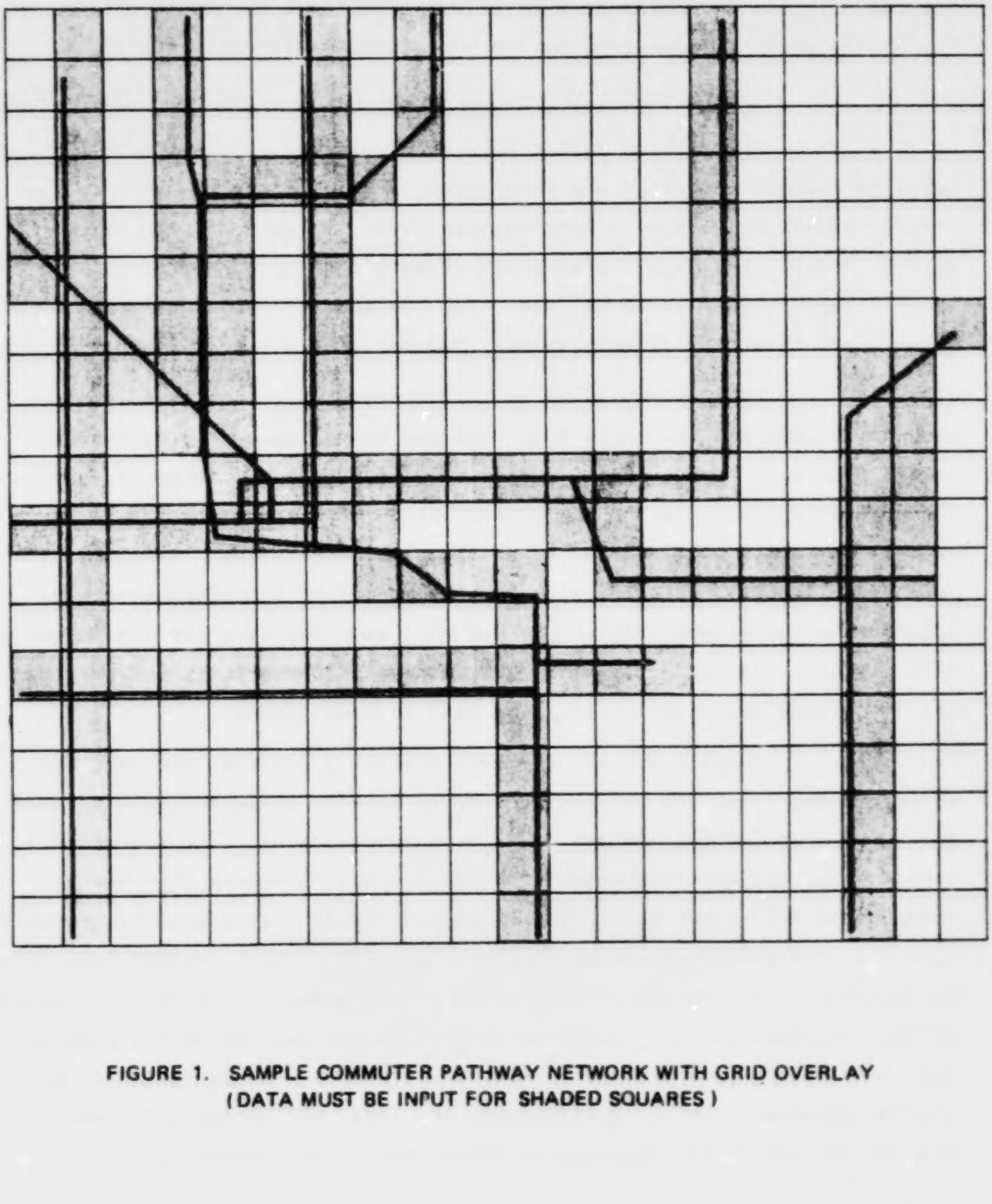

FIGURE 1. SAMPLE COMMUTER PATHWAY NETWORK WITH GRID OVERLAY
(DATA MUST BE INPUT FOR SHADED SQUARES)

roadway lengths and volumes need not be exact, because the primary network emissions and dispersion treatments involve a number of approximations.

The VMT for each grid square through which a commuter pathway passes will be input to the model and used to generate an emission rate for the square. Care should be taken so that the VMT on commuter pathways is not included in the VMT of a grid square.

In general, the results of the foregoing procedure will be used to compute emissions from the primary network. However, the model will allow the user to input an average daily emission rate for each grid square, in lieu of VMT. This option would be used when gridded emissions for the study area are readily available from another source or when the user has access to the projections generated by the Federal Highway Administration's (FHWA) battery of computer programs. In the latter case, the user may opt to run the APRAC-2 emissions module, which takes the FHWA historical traffic files as input (deleting, of course, the commuter pathways), to produce a gridded emission inventory. The values from this inventory may be used as input to the commuter exposure model. For further details on the APRAC-2 emissions module, see Ludwig, et al.[2]

c. Apportionment of Secondary Network VMT

The secondary traffic network consists of all streets not in the primary network or commuter pathways. The approach used for assigning secondary traffic to grid squares assumes that the ratio of secondary traffic to primary traffic varies by locale (or by land use). For instance, virtually all of the streets in the Central Business District (CBD) are likely to be important enough to be included in the primary traffic network. Similarly, very little traffic in rural areas is likely to be found off the major roadways. In residential and industrial areas, a large fraction of the the total traffic may use secondary streets. The user estimates the ratio of secondary to primary traffic for each locale type. The locale type of each grid square or group of grid squares for which data are required also will be input. The model will allot secondary network VMT on the grid squares in proportion to the product of the VMT on the primary network in that square and the ratio of the secondary to primary traffic associated with the locale type of the square. A list of locale types appears in Table 1.

Table 1

LOCALE TYPES

1. Central business district
2. Commercial areas in the core of the city, or suburban centers
3. Residential areas
4. Industrial areas
5. Rural and miscellaneous

If gridded emissions are input directly, as discussed in the previous section, secondary network emissions should be included in that inventory.

C. Traffic Modeling

Traffic modeling along commuter pathways requires the handling of two separate traffic flow regimes: uninterrupted flow and interrupted flow. Travel on expressways is generally uninterrupted, although during a backup, the flow can become severly constrained to the point of becoming "stop and go." Interrupted flow describes travel on arterials with traffic signals at the intersections.* The following discussion details those elements of the computer exposure model that describe the traffic flow. Figure 2 is a flowchart illustrating the traffic modeling procedure.

1. Uninterrupted Flow

The characteristics of uninterrupted flow can be obtained from two parameters, demand volume (v) and free-flow capacity (c) of the road segment. Both will be required inputs to the model. Demand volume may be obtained from volume flow maps or tabulated volume data available from the local transportation agency. Ideally, hourly data should be available, but often only the average daily traffic (ADT) or annual average daily traffic (AADT) can be obtained. In the latter cases, factors must be applied to arrive at estimated hourly volumes during commuting periods. Those factors should be obtained from the local transportation agency so that they are representative of the area. If they are unavailable, national average values should be used. As an example, Table 2 shows the percentage of weekday AADT by hour, land use type, and direction of travel on freeways in the San Francisco Bay Area. Table 3 supplies the same data for nonfreeway streets.

Seasonal adjustment factors are also needed to define how the AADT changes with season (winter incudes December-February, spring includes March-May, etc.). These data should be obtained for the local area under consideration.

The commuter exposure model will allow the input of hourly volumes directly, ADT, AADT, and the appropriate correction factors.

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*Intersections that have stop signs are not considered since they will not be present for the main traffic flow on an arterial, commuter pathway.

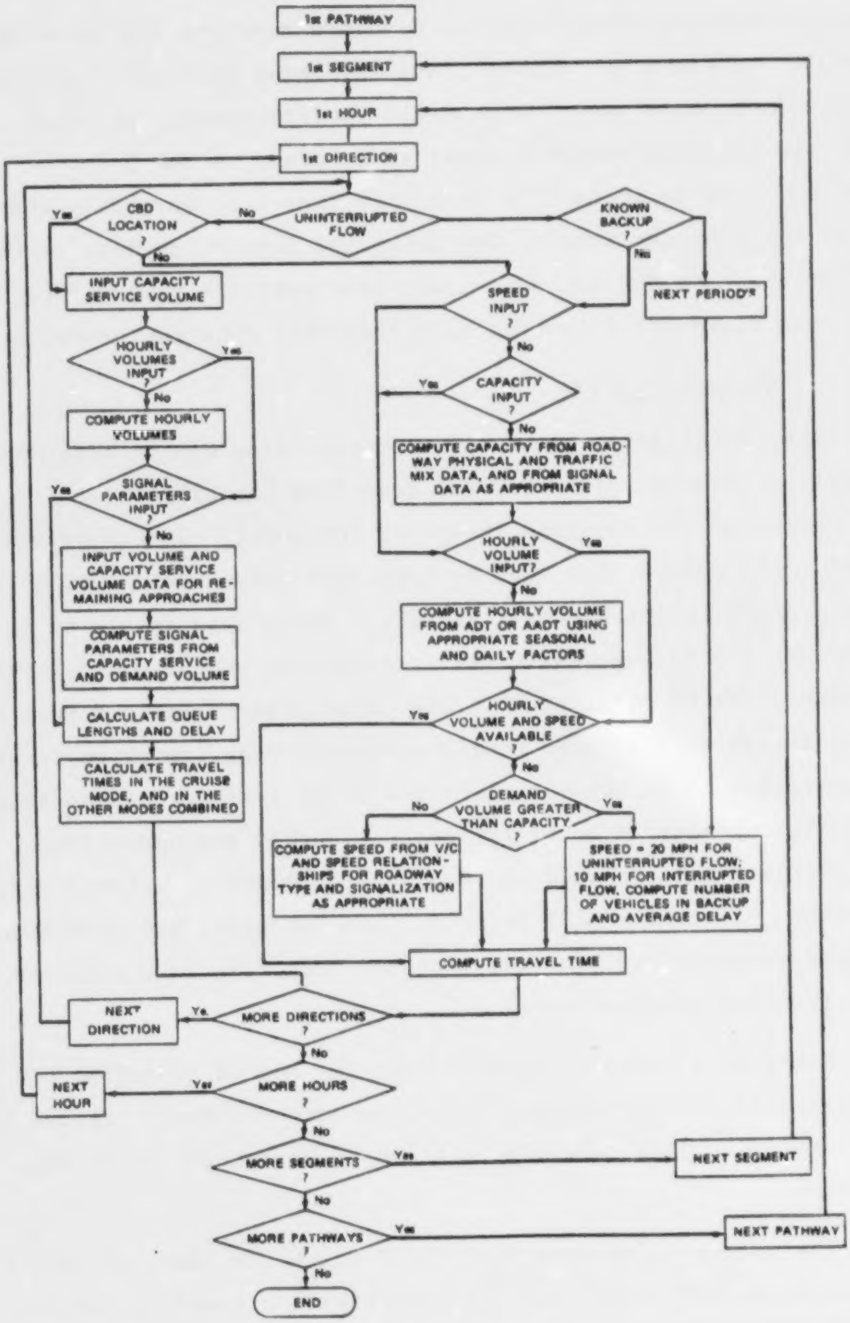

1st PATHWAY
1st SEGMENT
1st HOUR
1st DIRECTION
CBD LOCATION ?
Yes
No
UNINTERRUPTED FLOW
No
KNOWN BACKUP ?
No
NEXT PERIOD*
INPUT CAPACITY SERVICE VOLUME
SPEED INPUT ?
No
HOURLY VOLUMES INPUT ?
Yes
No
CAPACITY INPUT ?
Yes
No
COMPUTE HOURLY VOLUMES
COMPUTE CAPACITY FROM ROADWAY PHYSICAL AND TRAFFIC MIX DATA, AND FROM SIGNAL DATA AS APPROPRIATE
SIGNAL PARAMETERS INPUT ?
Yes
No
HOURLY VOLUME INPUT?
Yes
No
INPUT VOLUME AND CAPACITY SERVICE VOLUME DATA FOR REMAINING APPROACHES
COMPUTE HOURLY VOLUME FROM ADT OR AADT USING APPROPRIATE SEASONAL AND DAILY FACTORS
COMPUTE SIGNAL PARAMETERS FROM CAPACITY SERVICE AND DEMAND VOLUME
HOURLY VOLUME AND SPEED AVAILABLE ?
Yes
No
CALCULATE QUEUE LENGTHS AND DELAY
CALCULATE TRAVEL TIMES IN THE CRUISE MODE, AND IN THE OTHER MODES COMBINED
DEMAND VOLUME GREATER THAN CAPACITY ?
No
Yes
COMPUTE SPEED FROM V/C AND SPEED RELATIONSHIPS FOR ROADWAY TYPE AND SIGNALIZATION AS APPROPRIATE
SPEED = 20 MPH FOR UNINTERRUPTED FLOW; 10 MPH FOR INTERRUPTED FLOW. COMPUTE NUMBER OF VEHICLES IN BACKUP AND AVERAGE DELAY
COMPUTE TRAVEL TIME
NEXT DIRECTION
Yes
MORE DIRECTIONS ?
No
NEXT HOUR
Yes
MORE HOURS ?
No
MORE SEGMENTS ?
Yes
NEXT SEGMENT
No
MORE PATHWAYS ?
Yes
NEXT PATHWAY
No
END

FIGURE 2. FLOWCHART OF PATHWAY TRAFFIC MODELING PROCEDURE

Table 2

EXAMPLES OF WEEKDAY DIURNAL TRAFFIC CYCLES ON FREEWAYS IN THE SAN FRANCISCO BAY AREA

Hour Ending (local time)	CBD[*]		Commercial		Residential		Industrial		Rural	
	NB[†]	SB	NB	SB	NB	SB	NB	SB	EB	WB
00	.017	.014	.013	.012	.007	.017	.009	.012	.022	.011
01	.010	.007	.004	.006	.003	.005	.006	.006	.011	.006
02	.006	.004	.004	.004	.002	.003	.004	.004	.007	.005
03	.004	.004	.002	.001	.001	.001	.003	.003	.005	.004
04	.004	.006	.003	.001	.000	.001	.005	.004	.005	.007
05	.007	.016	.005	.005	.009	.001	.011	.008	.007	.023
06	.022	.062	.033	.026	.077	.009	.055	.047	.019	.110
07	.057	.097	.127	.079	.175	.041	.094	.069	.053	.117
08	.055	.075	.130	.086	.131	.049	.072	.053	.045	.083
09	.044	.052	.066	.049	.056	.034	.059	.052	.045	.061
010	.044	.051	.048	.039	.045	.032	.032	.055	.045	.054
011	.050	.054	.043	.040	.041	.034	.058	.056	.047	.049
012	.057	.049	.047	.043	.039	.035	.054	.052	.043	.045
013	.053	.056	.042	.046	.042	.035	.058	.061	.050	.046
014	.059	.063	.045	.052	.041	.043	.059	.063	.053	.050
015	.078	.067	.051	.071	.057	.070	.070	.073	.070	.050
016	.110	.072	.070	.091	.059	.163	.083	.088	.099	.065
017	.099	.064	.073	.103	.059	.181	.068	.097	.101	.058
018	.060	.047	.055	.074	.045	.101	.051	.067	.095	.042
019	.045	.039	.042	.048	.048	.051	.039	.041	.045	.037
020	.033	.027	.031	.035	.032	.028	.033	.029	.036	.021
021	.035	.027	.026	.033	.021	.024	.034	.026	.039	.019
022	.028	.026	.020	.029	.023	.025	.023	.018	.033	.021
023	.024	.022	.017	.025	.013	.017	.018	.019	.025	.017
Total	1.001	1.001	.998	.998	1.001	1.000	.998	1.003	1.000	1.001

[*] These data are from Seattle; others are San Francisco Bay Area Locales.

[†] Directions:
NB = Northbound
SB = Southbound
EB = Eastbound
WB = Westbound

Table 3

EXAMPLES OF WEEKDAY DIURNAL TRAFFIC CYCLES ON NONFREEWAY STREETS IN THE SAN FRANCISCO BAY AREA

Hour Ending (local time)	CBD[*]		Commercial		Residential		Industrial		Rural	
	NB[†]	SB	EB	WB	NB	SB	EB	WB	EB	WB
00	.013	.015	.008	.014	.006	.021	.015	.010	.007	.016
01	.006	.008	.004	.007	.003	.010	.007	.004	.002	.009
02	.003	.006	.003	.005	.002	.005	.005	.004	.002	.005
03	.004	.004	.002	.003	.002	.003	.004	.002	.001	.002
04	.002	.004	.002	.002	.003	.002	.002	.005	.012	.004
05	.003	.007	.007	.002	.015	.003	.004	.018	.012	.003
06	.017	.027	.036	.010	.078	.009	.024	.066	.056	.017
07	.035	.061	.101	.031	.149	.033	.086	.103	.161	.054
08	.036	.052	.081	.041	.077	.036	.057	.079	.091	.046
09	.039	.040	.051	.038	.059	.034	.049	.001	.058	.037
010	.048	.050	.052	.046	.052	.040	.051	.057	.058	.051
011	.067	.059	.057	.055	.051	.053	.053	.057	.055	.052
012	.104	.078	.064	.068	.052	.057	.057	.056	.045	.048
013	.068	.081	.066	.060	.049	.064	.064	.056	.052	.051
014	.070	.070	.061	.064	.058	.067	.067	.061	.062	.057
015	.071	.066	.065	.073	.071	.074	.074	.062	.066	.073
016	.095	.077	.068	.097	.056	.099	.099	.079	.064	.127
017	.081	.072	.052	.121	.052	.079	.079	.065	.059	.125
018	.057	.049	.052	.081	.055	.052	.052	.054	.054	.063
019	.048	.043	.052	.058	.043	.036	.036	.031	.032	.035
020	.046	.047	.045	.035	.021	.032	.032	.019	.017	.030
021	.039	.036	.028	.038	.017	.039	.039	.018	.012	.040
022	.028	.026	.025	.031	.017	.027	.027	.016	.019	.031
023	.020	.021	.018	.019	.011	.019	.019	.016	.015	.022
Total	1.000	0.999	1.000	0.999	0.999	1.002	1.002	0.999	1.001	0.998

[*] These data are from Seattle, others are San Franciosco Bay Area Locales.

[†] Directions:

NB = Northbound
SB = Southbound
EB = Eastbound
WB = Westbound

Typical values of the correction factors will be built into the model as default parameters. The user of the model will then be able to tell the model the form of data that are being input, and will also have default correction factors available if necessary.

The capacity of a roadway is defined in the Highway Capacity Manual as "the maximum number of vehicles which has a reasonable expectation of passing over a given section of a lane or a roadway in one direction (or in both directions for a two-lane or a three-lane highway) during a given time period under prevailing roadway and traffic conditions". Usually, capacity pertains to a one-hour period. Capacity will vary along segments of a commute pathway because of physical characteristics, the makeup of the traffic, weather conditions, accidents, and so forth.

For the commuter exposure model, capacity can be estimated by the following techniques. If the local transportation agency can provide better estimates, such as from field study results, those data should be used. The Highway Capacity Manual gives the following maximum uninterruped flow capacities under ideal conditions for various types of roadways:

Highway Type	Capacity
Multilane	2,000 per lane
Two-lane, two-way	2,000 total (both directions)
Three-lane, two-way	4,000 total (both directions)

The capacity, C, of a multilane roadway is computed with the following equation:

$$C = 2000\ MWf\ T;$$

the capacity for one direction of a two-lane roadway is computed with the equation:

$$C = 1000\ WfT$$

where

M = number of lanes moving in one direction
Wf = adjustment factor for lane width from Table 4
T = truck factor from Table 5 .

The entries in Tables 4 and 5 will be included in the model. The user will be provided the option of entering capacity directly, or the type of roadway, lane width, lateral clearance, and percentage of trucks for each segment so that the appropriate factors can be called in the model.

Once volume and capacity are known for a freeway or expressway, the speed at which traffic moves may be determined. Figures 3 and 4 show the relationships between the ratio of volume to capacity and the operating speed in one direction of travel and under uninterrupted flow conditions for freeways and expressways and for multilane rural highways. Figure 5 depicts similar relationships for both directions of travel on two-lane rural highways. The equations to those curves will be functions or will be in subroutines in the model. Given volume and capacity, the operating speed would then be calculated for use in calculations of emissions and travel or exposure time.

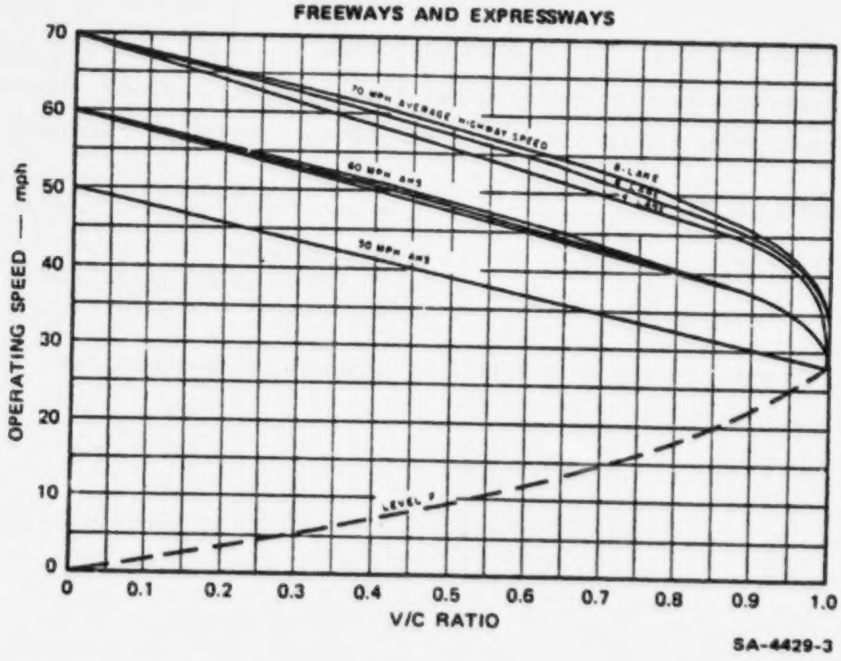


FIGURE 3 RELATIONSHIPS BETWEEN V/C RATIO AND OPERATING SPEED, IN ONE DIRECTION OF TRAVEL, ON FREEWAYS AND EXPRESSWAYS, UNDER UNINTERRUPTED FLOW CONDITIONS

Table 4

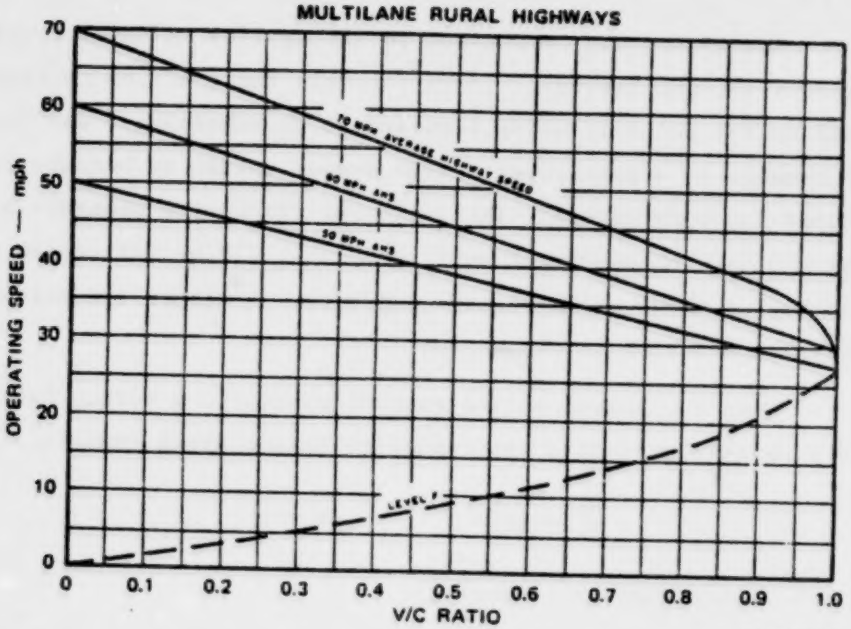
COMBINED EFFECT OF LANE WIDTH AND RESTRICTED LATERAL CLEARANCE ON CAPACITY AND SERVICE VOLUMES OF DIVIDED FREEWAYS AND EXPRESSWAYS AND TWO-LANE HIGHWAYS WITH UNINTERRUPTED FLOW

Distance from Traffic Lane Edge to Obstruction	Adjustment Factor, Wf, for Lane Width and Lateral Clearance							
	Obstruction of One Side of One-Direction Roadway				Obstructions on Both Sides of One-Direction Roadway			
	12-ft lanes	11-ft lanes	10-ft lanes	9-ft lanes	12-ft lanes	11-ft lanes	10-ft lanes	9-ft lanes
Four-Lane Divided Freeway, One Direction of Travel								
6	1.00	0.97	0.91	0.81	1.00	0.97	0.91	0.81
4	0.99	0.96	0.90	0.80	0.98	0.95	0.89	0.79
2	0.97	0.94	0.88	0.79	0.94	0.91	0.86	0.76
0	0.90	0.87	0.82	0.73	0.81	0.79	0.74	0.66
Six- and Eight-Lane Divided Freeways, One Direction of Travel								
6	1.00	0.96	0.89	0.78	1.00	0.96	0.89	0.78
4	0.99	0.95	0.88	0.77	0.98	0.94	0.87	0.77
2	0.97	0.93	0.87	0.76	0.96	0.92	0.85	0.75
0	0.94	0.91	0.85	0.74	0.91	0.87	0.81	0.70
Two-Lane Highway, One Direction of Travel								
6	1.00	0.88	0.81	0.76	1.00	0.88	0.81	0.76
4	0.97	0.85	0.79	0.74	0.94	0.83	0.76	0.71
2	0.93	0.81	0.75	0.70	0.85	0.75	0.69	0.65
0	0.88	0.77	0.71	0.66	0.76	0.67	0.62	0.58

Table 5

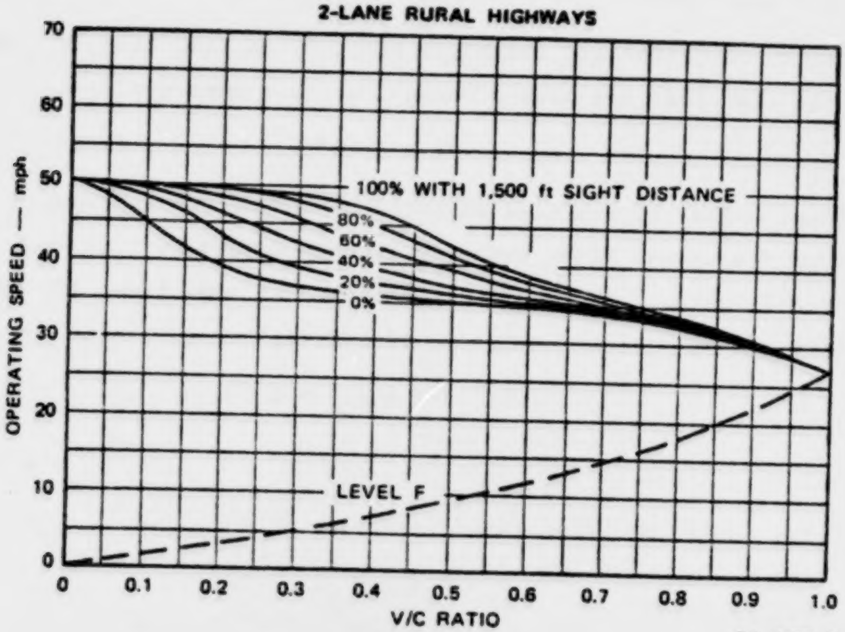
AVERAGE GENERALIZED ADJUSTMENT FACTORS FOR TRUCKS ON FREEWAYS AND EXPRESSWAYS, AND TWO-LANE HIGHWAYS OVER EXTENDED SECTION LENGTHS

Pt, Percentage of Trucks (%)	Factor, T, For All Levels of Service		
	Level Terrain	Rolling Terrain	Mountainous Terrain
	Freeways and Expressways		
1	0.99	0.97	0.93
2	0.98	0.94	0.88
3	0.97	0.92	0.83
4	0.96	0.89	0.78
5	0.95	0.87	0.74
6	0.94	0.85	0.70
7	0.93	0.83	0.67
8	0.93	0.81	0.64
9	0.92	0.79	0.61
10	0.91	0.77	0.59
11	0.89	0.74	0.54
14	0.88	0.70	0.51
16	0.86	0.68	0.47
18	0.85	0.65	0.44
20	0.83	0.63	0.42
Two-Lane Highways			
1	0.99	0.96	0.90
2	0.98	0.93	0.82
3	0.97	0.89	0.75
4	0.96	0.86	0.69
5	0.95	0.83	0.65
6	0.94	0.81	0.60
7	0.93	0.78	0.57
8	0.93	0.76	0.53
9	0.92	0.74	0.50
10	0.91	0.71	0.48
12	0.89	0.68	0.43
14	0.88	0.64	0.39
16	0.86	0.61	0.36
18	0.85	0.58	0.34
20	0.83	0.56	0.31



SA-4429-4

FIGURE 4 RELATIONSHIPS BETWEEN V/C RATIO AND OPERATING SPEED, IN ONE DIRECTION OF TRAVEL, ON MULTILANE RURAL HIGHWAYS, UNDER UNINTERRUPTED FLOW CONDITIONS



SA-4429-5

FIGURE 5 RELATIONSHIPS BETWEEN V/C RATIO AND OPERATING SPEED, OVERALL FOR BOTH DIRECTIONS OF TRAVEL, ON TWO-LANE RURAL HIGHWAYS WITH AVERAGE HIGHWAY SPEED OF 50 MPH, UNDER UNINTERRUPTED FLOW CONDITIONS

The methodology described so far applies to uninterrupted flow on freeways and expressways. It is possible for the flow to become constrained to the point of being stop-and-go on expressways and freeways, either because of a particularly high demand volume or because capacity is reduced for some reason. The following discussion presents a method for calculating the number of vehicles that would be influenced by a traffic backup when volume exceeds capacity. A method for calculating average exposure time is also given.

When the demand volume exceeds capacity, a backup builds up in the congested area at a rate equal to demand minus capacity:

$$\frac{dn}{dt} = q-s \qquad q > s$$

where n = size of backup (vehicles)

q = demand volume over a suitable averaging time, (vehicles/sec)

s = capacity of the particular section of the road on which the backup occurs (vehicles/sec)

t = time (sec)

The backup increases and reaches a size, N, at some time, t', measured from the time that the backup begins $(q > s)$, when $q = s$:

$$N = (q-s)t'.$$

The total number of vehicles affected by congestion includes N plus those entering the backup after capacity exceeds demand $(s > q)$, but before the backup dissipates. The backup is relieved at some time, t'', measured from the time when $q = s$; $(t'' = t-t')$, satisfying

$$st'' - N - qt'' = 0$$

$$t'' = \frac{N}{s-q} \qquad s > q.$$

The total number of vehicles affected is

$$\hat{N} = N + qt''$$

$$= N + \frac{qN}{s-q} = \frac{sN - qN + qN}{s-q}$$

$$\hat{N} = \frac{N}{1-q/s}.$$

Note that the numerator is evaluated for the time that $q > s$, while the denominator is evaluated during $s > q$. Note also that q is the demand volume over a suitable averaging time that is representative of the transiency of the backup.

The "delay", or time spent traversing the backup, is a function of the length of the backup and the average travel speed:

$$D = D(n,v).$$

Assuming each vehicle occupies a constant k meters,

$$D = \frac{kn}{v},$$

and assuming that the average speed is constant, then the change in delay to vehicles entering the backup at different times is

$$dD = \frac{kn}{v}\,dn,$$

and the total delay for all vehicles is

$$\int dD = \int \frac{kn}{v}\,dn.$$

Calling the total delay D, we have

$$D = \int_0^N \frac{kn}{v}\,dn.$$

For $q > s$, $n = (q-s)t$ and $dn = d\left[(q-s)t\right] = (q-s)dt$, since q and s are also assumed constant. Then

$$D = \int_0^T \frac{k(q-s)^2 t\,dt}{v} = \left.\frac{k(q-s)^2t^2}{2v}\right|_0^T$$

where $T = N/(q-s)$. The average delay is D/N, or $D/\int_0^T (q-s)dt$

$$D_{avg} = \frac{\left.\frac{k(q-s)^2t^2}{2v}\right|_0^T}{\left.(q-s)t\right|_0^T} = \left.\frac{k(q-s)t}{2v}\right|_0^T$$

$$= \frac{k(q-s)T}{2v}$$

$$\text{or } \frac{kN}{2v}.$$

The average delay when s > q is calculated in the same manner. In this case, the number of vehicles in the backup is

$$n = N - (s-q)t$$

$$\text{and } dn = -(s-q)dt.$$

Then

$$D = \int_{N}^{0} \frac{kn}{v}\, dn$$

$$= -\int_{T'}^{0} \frac{k\left[N-(s-q)t\right](s-q)dt}{v}$$

and the total delay can be calculated from

$$D = -\left.\frac{kN(s-q)t}{v}\right|_{T''}^{0} + \left.\frac{k(s-q)^2t^2}{2v}\right|_{T''}^{0}$$

where T" is the time for the backup to dissipate. Since T" equals N/(s-q), the total delay for vehicles arriving when s > q is

$$D = \frac{kN^2}{v} - \frac{kN^2}{2v}$$

$$= \frac{kN^2}{2v}$$

The average delay per vehicle is

$$D_{avg} = \frac{kN^2}{2v(\hat{N}-N)}.$$

The total delay when q > s equals the total delay when s > q. The average delay for all vehicles is then

$$D_{avg} \text{ (all vehicles)} = \left(\frac{kN^2}{2v} + \frac{kN^2}{2v}\right) \div \hat{N}$$

$$= \frac{kN^2}{v\hat{N}}$$

As an example, consider the data below, giving five-minute demand volumes on a roadway with a capacity of 2000 vehicles/hr, 167 vehicles/five minutes, or .55 veh/sec:

Five-Minute Increment	Demand Volume
1	167
2	200
3	200
4	210
5	180
6	190
7	180
8	150
9	110
10	100

In increment 1, demand equals capacity, and no backup occurs. In increments 2-7, demand exceeds capacity. The average demand is 1160 vehicles/1800 sec, or .64 veh/sec.

The number of vehicles backed up during this period is then

$$\begin{aligned} N &= (q - s)t' \\ &= (.64 - .55)\ 1800 \\ &= 160 \text{ vehicles.} \end{aligned}$$

During the next 15 minutes, the additional vehicles backed up equals

$$\frac{qN}{s-q} = \frac{(.40)(160)}{.55 - .40} = 411 \text{ vehicles.}$$

The total is

$$160 + 411 = 571 \text{ vehicles.}$$

The time for the backup to clear up is given by $t'' = \frac{N}{s-q}$

$$= \frac{160}{.55 - .40} = 1029 \text{ seconds} = 17.1 \text{ minutes.}$$

Assuming that vehicles in the congested area are able to maintain an average speed of 20 mi/hr, and assuming a time headway of 1.8 sec, each vehicle "occupies" 16 meters. The time for the 160th vehicle to pass through the congested area is

$$\frac{(160\ \text{vehicles})(16\text{m/vehicle})}{(20\text{mi/hr})(0.447\text{m/sec/mi/hr})} = 286\ \text{sec.}$$

$$= 4\ \text{min, } 46\ \text{sec.}$$

Assuming a 2-second headway yields

$$\frac{(160)(18\text{m/vehicle})}{(20)(0.447)} = 5\ \text{min, } 22\ \text{sec.}$$

This example shows that, first of all, the calculation of the total queue length produces a conservative estimate. During the last three five-minute increments, 360 vehicles approach the congested area, while the calculation indicates that 411 vehicles enter the backup. Also, the time for the congestion to break up is presented as 45 minutes, while the calculated time is 30 + 17.1 minutes, or 47.1 minutes. This extended time and the conservative calculation of the number of vehicles affected are directly related.

Figure 6 indicates that the maximum time for a vehicle to pass through the congested area is just under five minutes. The calculated values of 4.8 and 5.4 minutes agree reasonable well with this time.

The "delay", or the time for vehicles to traverse the backup is, for $q > s$,

$$D = \frac{8(.64 - .55)^2 1800^2}{(20)(.44704)}^{*}$$

$= 22906$ vehicle sec

or 143.2 sec average per vehicle;

for $s > q$

$$D = \frac{8(.55 - .40)^2 1029^2}{(20)(.44704)}^{*}$$

$= 22906$ vehicle sec

or 55.7 sec/average vehicle

The average over the life of the backup is

$$\frac{2(22906)}{(160 + 411)} = 80.23\ \text{sec average per vehicle}$$

---

* Some of the numbers in this equation have been rounded.

The equations presented above for backup conditions occurring when demand volume exceeds capacity will be included in the commuter exposure model. That is important for modeling worst-case exposures, as well as for providing a more realistic indication of overall commuter exposure. The example calculations apply to one lane of traffic; a four-lane expressway with similar conditions in each lane would have a backup involving 2,284 vehicles.

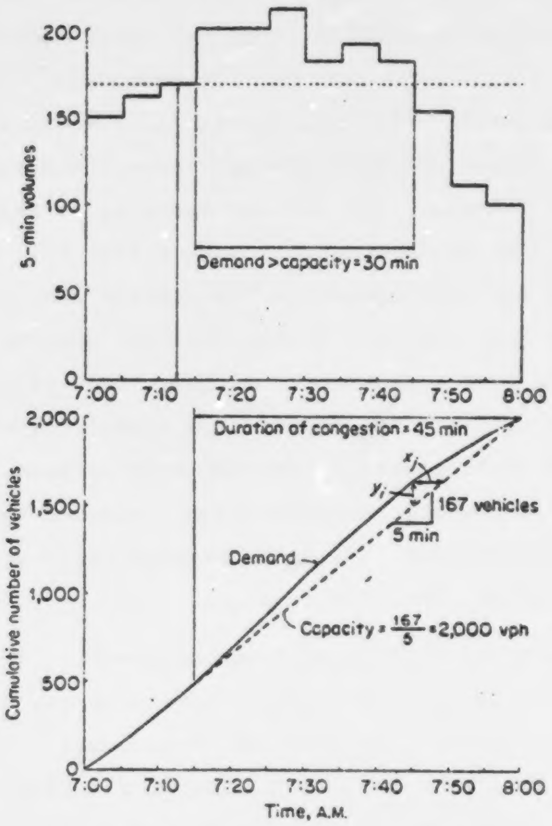


FIGURE 6 Relation between demand, capacity, and congestion.[3]

2. Interrupted Flow

Interrupted flow pertains to traffic conditions when movement is routinely stopped, or interrupted, for a finite period of time. For the purposes of a commuter exposure model, only two causes of interrupted flow need be considered: signalized intersections and toll booths. At those two locations of interrupted flow, traffic goes through mode changes from cruise to deceleration, idle, acceleration, and back to cruise. Emissions, and hence concentrations, and times of exposure are influenced by those mode changes.

Comparisons of emissions estimates made using the Modal Analysis Model[4] and the FTP methodology[5] have shown good agreement except at low average route speeds. That is to be expected because as the average route speed increases, more driving time is spent at or near the average route speed, and there are fewer changes of driving mode. At lower speeds, however, there is an increasing array of mode and speed combinations that can produce the same average speed, and the FTP methodology does not fully account for that. As a result, the commuter exposure model will include traffic modeling capabilities for both average route speed and mode changes for interrupted flow conditions. The average route speed methodology will be used outside of the CBD, while the modal methodology will be used inside of the CBD. The reason for this choice is that speeds are likely to be lowest and mode changes most frequent within the CBD, and the difference among emission estimates most pronounced. Although the use of the average route speed/FTP methodology for interrupted flow conditions outside of the CBD does not provide the spatial detail that the modal treatment can give, that is not crucial for a commuter exposure model, because exposure is time-integrated along the pathway. Using an average route speed temporally smooths emissions instead of concentrations.

Average route speed will be an input parameter. The local transportation agency should be able to offer advice on average route speed estimates for interrupted flow portions of pathways. As a default, the curves in Figure 7 should be fit to equations for inclusion in the model. The curves rely on volume-to-capacity ratios as input, and they estimate an average speed for coordinated and uncoordinated traffic signals. As a comparison with Figure 7, which is based on national data, Figure 8 shows site-specific curves specifically for the Washington, D.C. metropolitan area.[6] If a transportation agency cannot supply average speed data, they may be able to provide curves similar to those in Figure 8, but based on data from the local region.

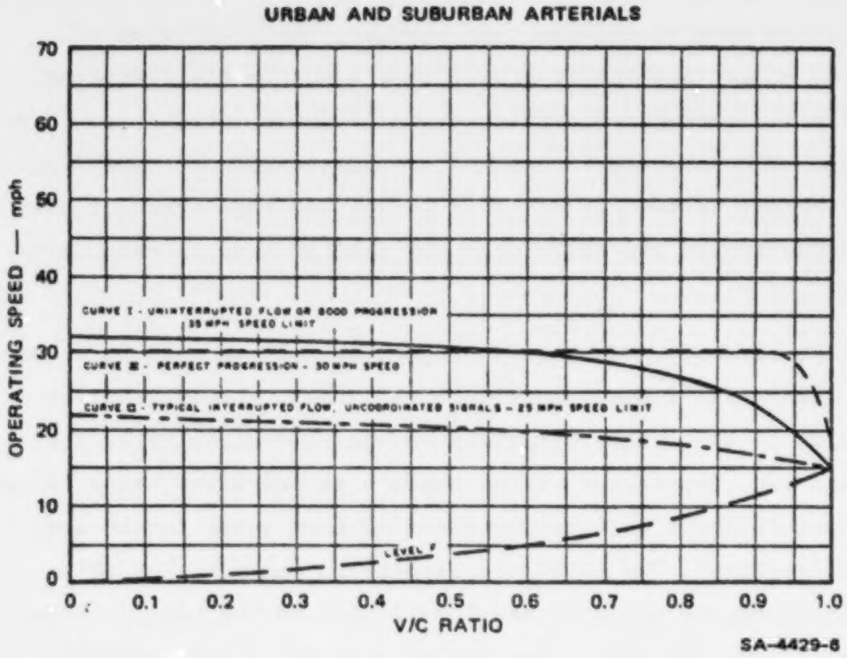


FIGURE 7 TYPICAL RELATIONSHIPS BETWEEN V/C RATIO AND AVERAGE OVERALL TRAVEL SPEED, IN ONE DIRECTION OF TRAVEL, ON URBAN AND SUBURBAN ARTERIAL STREETS

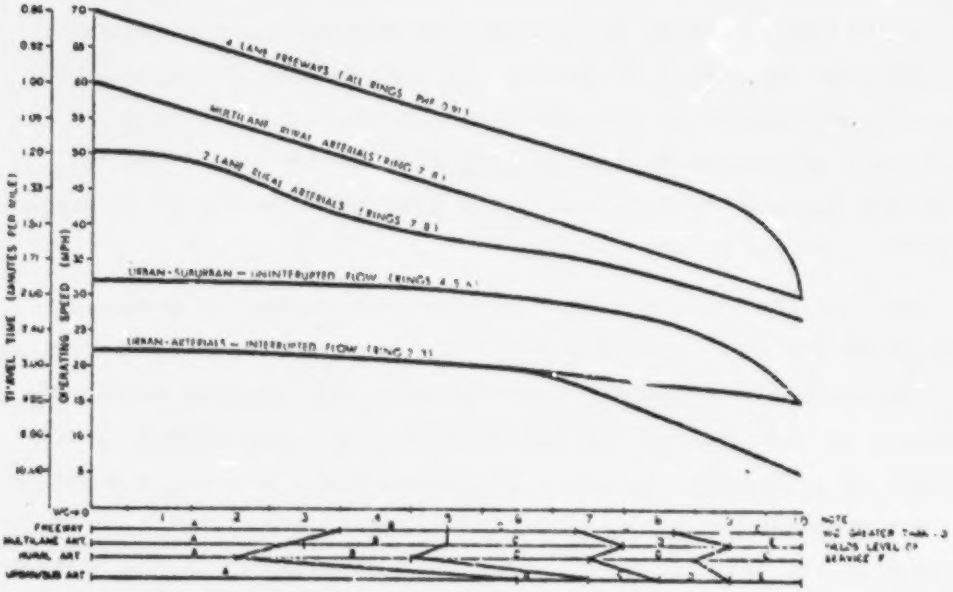


FIGURE 8 OPERATING SPEED RELATED TO LEVEL OF SERVICE, ROUTE TYPE VOLUME/CAPACITY RATIO AND RING

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A more thorough analysis is warranted for CBD pathway segments. Calculations must be made of driving mode changes, the proportion of vehicles changing modes, and the length of time spent in the different modes. Basically, that requires a calculation of queue lengths and delay at intersections. The parameters required are demand volume, capacity, and the traffic signal parameters of cycle length and the length of the green phase. Queue length and delay data can then be used to calculate modal emissions.

Ideally, capacity, volume, and signal parameters will be obtained from the local agency and input directly to the model. However, given the demand volumes on the intersection approaches, the geometry of the intersection, and the composition of the traffic as described below, first the capacity and then the signal parameters (and then queue length and delay) can be calculated. The following discussion explains how this may be done. The commuter exposure model will call on the user to supply capacity, but will have the default option of performing the remaining calculations of signal parameters.

Any at-grade intersection approach has a capacity that represents the maximum number of vehicles that can be accommodated, given the particular geometry, environment, and traffic characteristics and controls. The capacity service volume of an intersection approach is the maximum number of vehicles that can pass through the intersection during one hour of green time. The number of vehicles that can clear the intersection from an approach during one hour of elapsed time can be calculated by multiplying the fraction of the total cycle time that the signal is green by the capacity service volume.

The capacity service volume in vehicles per hour of green is determined using the nomograph, Figure 9. The user must know the percentage of trucks and buses, left turners, right turners, the location within the metropolitan area, the size of the metropolitan area, and whether or not the intersection is located in the CBD. The nomograph provides a solution for a two-way urban street with parking. The solution for that type of interesection is the most conservative estimate of capacity in the Highway Capacity Manual. If a street has no parking within 250 feet of the interesection, eight feet can be added to the curb-to-center line width

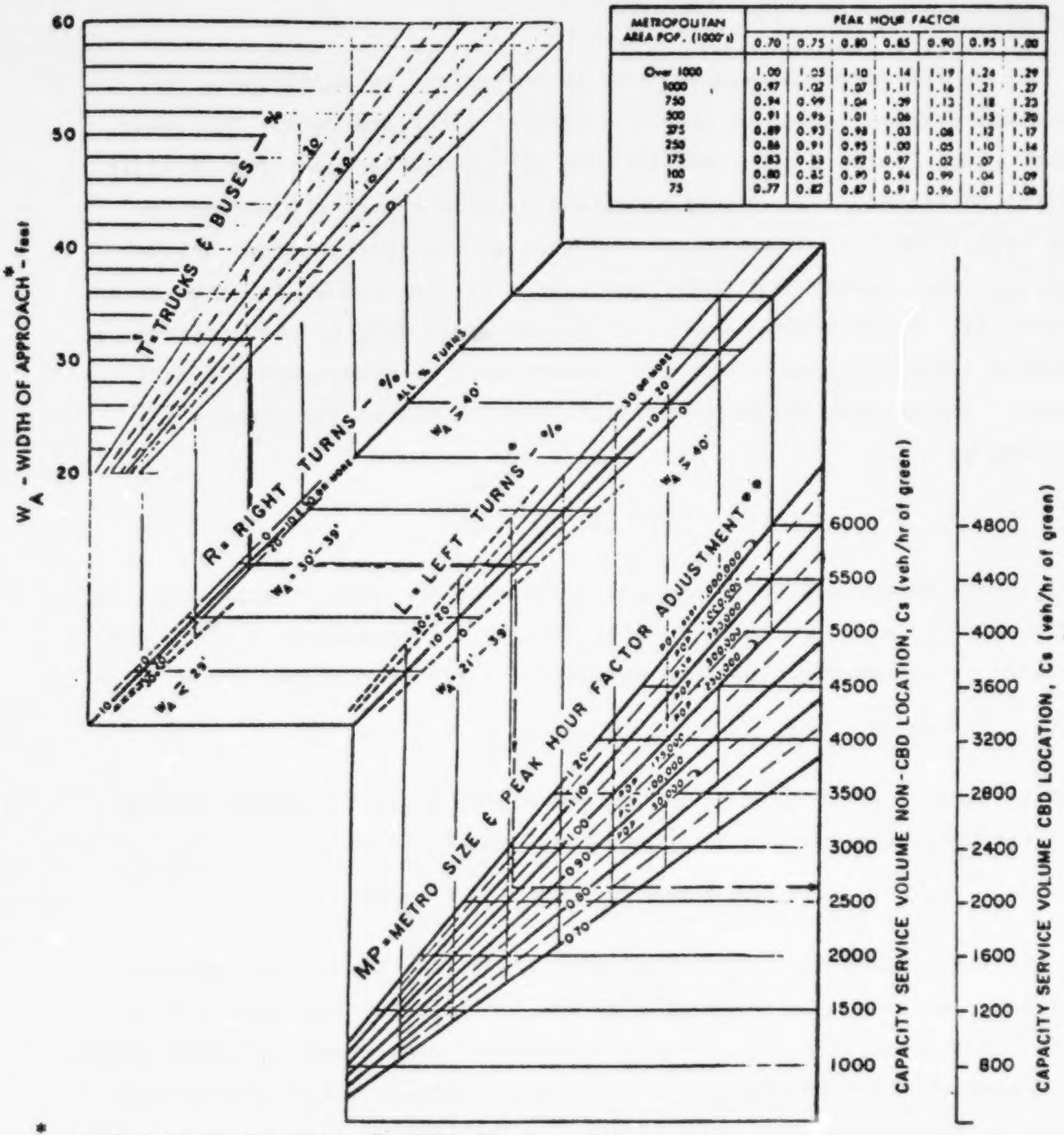

TABLE 8 MP = METROPOLITAN SIZE AND PEAK HOUR FACTOR ADJUSTMENT

METROPOLITAN AREA POP. (1000's)	PEAK HOUR FACTOR						
	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Over 1000	1.00	1.05	1.10	1.14	1.19	1.24	1.29
1000	0.97	1.02	1.07	1.11	1.16	1.21	1.27
750	0.94	0.99	1.04	1.09	1.13	1.18	1.23
500	0.91	0.96	1.01	1.06	1.11	1.15	1.20
375	0.89	0.93	0.98	1.03	1.08	1.12	1.17
250	0.86	0.91	0.95	1.00	1.05	1.10	1.14
175	0.83	0.88	0.92	0.97	1.02	1.07	1.11
100	0.80	0.85	0.90	0.94	0.99	1.04	1.09
75	0.77	0.82	0.87	0.91	0.96	1.01	1.06

* Add 8 feet to the approach width if there is no parking.

** When the peak hour factor is known, use table above to determine MP; when peak hour factor is not known use population directly.

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FIGURE 9 SERVICE VOLUME OF A SIGNALIZED INTERSECTION APPROACH

(Wa) and a conservative solution will still result from use of the nomograph.

The approach capacity, C, is determined by multiplying the capacity service volume by the G/Cy ratio for the approach. The green phase time, G, and cycle time, Cy, are determined by Webster's "Traffic Signal Settings".[7] Webster's equations provide enough cycle time for the vehicle demand volume to proceed through the intersection; however, the user must ensure that G for each phase is long enough for pedestrian crossings. To determine Webster's optimum cycle length, the critical or maximum volume to capacity service volumes must be determined for each phase. The maximum volume to capacity service volume for phase i is written as

$$\underset{i}{\text{Max}}\left[V_{i,j}/Cs_{i,j}\right]$$

and refers to those V/Cs ratios for approaches or lanes of approaches on which traffic moves on phase i. For example, if approaches 1 (i=1) and 3 (i=3) to an intersection move on phase 1 (j=1) of a signal, then

$$\underset{i}{\text{Max}}\left[V_{i,j}/Cs_{i,j}\right] = \text{Max}\left[V_{1,1}/Cs_{1,1},\ V_{3,1}/Cs_{3,1}\right] ,$$

and if phase 1 above is a left-turn phase, and phase 2 controls through and right-turning traffic on Approaches 1 and 3, then

$$\underset{i}{\text{Max}}\left[V_{i,j}/Cs_{i,j}\right] = \text{Max}\left[V_{1,2}/Cs_{1,2},\ V_{3,2}/Cs_{3,2}\right] .$$

In the above example, $V_{1,1}$ is the left-turn volume demand for Approach 1 and $Cs_{1,1}$ is the capacity service volume for left-turning traffic from Approach 1; similarly, $V_{1,2}$ is the through and right-turning volume demand for Approach 1 and and $Cs_{1,2}$ is the capacity service volume for through and right-turning traffic on Approach 1. The optimum signal cycle length is determined using the following equation:

$$Cy = \frac{(9\ Np + 5)}{1 - \sum\limits_{\text{all } j}\ \underset{i}{\text{Max}}\left[V_{i,j}/Cs_{i,j}\right]}$$

where

Np = the number of amber intervals per signal cycle during which there is no simultaneous green phase.

9 = a constant representing a weighted lost time in which three seconds of amber time and three seconds of start-up time are assumed.

$V_{i,j}$ = the volume on the i^{th} approach that moves during the j^{th} signal green phase.

$Cs_{i,j}$ = the capacity per hour of green to vehicles on the i^{th} approach moving during the j^{th} signal phase.

The green phase length is a fraction of the signal cycle time minus the total amber time. A three-second amber time is assumed for all green phases. (A three-second amber time is usually adequate for roadways with a speed limit less than or equal to 35 mi/hr. A four-second amber time is applicable for speeds of 35 to 50 mi/hr, and a five-second amber time is applicable beyond 50 mi/hr.) The green phase length of phase j is given by the following equation:

$$G_j = Cy \frac{\underset{i}{\text{Max}} \left[v_{i,j}/Cs_{i,j} \right]}{\sum\limits_{\text{all } j} \underset{i}{\text{Max}} \left[V_{i,j}/Cs_{i,j} \right]} - 3$$

where

- $\underset{i}{\text{Max}} \left[V_{i,j}/Cs_{i,j} \right]$ is the maximum V/Cs ratio on all approaches i moving on green phase j.
- 3 is an assumed 3-sec amber time
- $\sum\limits_{\text{all } j} \left[V_{i,j}/Cs_{i,j} \right]$ is the sum of the V/Cs ratios that control the green phase durations.

The approach capacity is found by multiplying the approach capacity service volume by the appropriate green to cycle ratio and summing for all applicable phases. Since an approach is considered to be one direction of flow into an intersection, separate left-turning, through, and right-turning signal phases affecting one approach should have their capacities added together to determine the total capacity of an approach. The capacity of an approach is given as follows:

$$C_i = \sum_j Cs_{i,j}\ Gj/Cy$$

where j are those green signal phases that allow traffic to move on intersection approach i.

Examples of controllers for which this methodology is applicable are three-and four-phase controllers, which have a preceding left-turn green indication, three-and four-phase controllers with one or two left-turn phases, and eight-phase controllers with possible overlapping left-turn and through phases (i.e., multiple phases) on all opposing approaches. Usually the signal cycle time is the sum of the green phase times and amber times for all phases. When overlapping phases occur, the cycle time is the sum of the left turn and through phases plus amber time, when there is no simultaneous green indicator. The capacity of an approach is the sum of the capacities for each through or turning movement on the approach.

Once capacity, volume, and the signal parameters are known, the proportion of vehicles that stop for a signal is given by

$$P = \frac{1-G/Cy}{1-V/Cs}$$

where G = length of the green phase
Cy = signal cycle length
V = hourly demand volume
Cs = capacity service volume per hour of green.

The number (N) of vehicles subject to queueing delay is:

$$N = \frac{P\ V\ Cy}{3600}$$

while the maximum length of the queue (Lq, m) is:

$$Lq = 8N/M$$

where 8 is the distance (meters) occupied by each queued vehicle and M is the number of lanes in the approach. On the average, a stopped vehicle waits one-half the length of the red phase, so the average delay to those vehicles is

$$D = 0.5\ (Cy-G).$$

For toll booths, the methodology is different because all vehicles must stop and wait to be served. The average number of vehicles waiting to leave a toll booth is computed from classical queueing theory as

$$N = \frac{V}{C-V}.$$

The queue length in meters is

$$Lq = \frac{8N}{M}\ .$$

The average delay for vehicles at a toll booth is the queue length (vehicles) multiplied by the average service rate, or inverse of capacity:

$$D = \frac{3600\ N}{C}.$$

Note that this applies to all vehicles because all must stop.

The methodology presented in this section has been demonstrated for air pollution work in a number of studies. While there are other more complicated methods of handling traffic flow modeling, the approach recommended here has been found to be quite suitable for air pollution work.

When the commute paths enter the CBD, and the queueing calculations are applied, single routes must be chosen for each commute path, terminating at a reasonable location. This could be a central point in the CBD, or there could be a separate terminus for each path, such as locations of relatively high employment density within the urban core. For paths not going to the CBD, the end points should be clear because they had to have been identified already in order to support a commute path not involving the CBD.

D. Emissions Modeling

The model user will have the option of inputing emission rates for each pathway segment and grid square directly or of having the model compute the emission rates. If emissions are to be computed, two types of emissions treatments are required of the commuter exposure model: a treatment based on the average route speed, and one that considers the effects of driving mode changes on emissions. The first treatment is given by the familiar FTP procedure.[5] The second treatment will use the "Automobile Exhaust Emission Modal Analysis Model,"[4] or modal model. Emissions modeling along pathways requires both treatments; FTP-based emissions estimates are suitable for non-pathway sources.

1. Emissions on Pathways

Figure 10 is a flowchart illustrating the modeling procedures for pathway emissions. FTP emission factors will be used for pathway segments that are freeways, expressways, or arterials outside the CBD. The FTP methodology requires the following input parameters as a minimum: altitude, state (California or other), calendar year, vehicle model year mix, and vehicle type mix. Vehicle mix data may be obtained for a given location from state or county agencies or from R. L. Polk, or national average data may be used.

The basic FTP emission factors assume an average route speed of 19.6 mi/hr, an ambient temperature of about 75°F, and 20 percent cold-starting, 27 percent hot-starting, and 53 percent hot-transient vehicles. When conditions depart from these assumed values, a combined speed-temperature-cold start correction factor will be applied. All other FTP correction factors (e.g., air conditioning, trailer towing) will be assumed to have a value of unity.

For the purposes of the commuter exposure model, it will be assumed that no vehicles are operating in the cold-start mode while they are on freeways, expressways, or pathways outside of the CBD. While cold-start emissions might affect background concentrations by their impact on network-wide emissions, travel to the pathways in the morning is assumed to take place on roadways having relatively low on-roadway concentrations. In the evening, vehicles are assumed to be warmed up by the time they leave the CBD or enter a freeway or expressway.

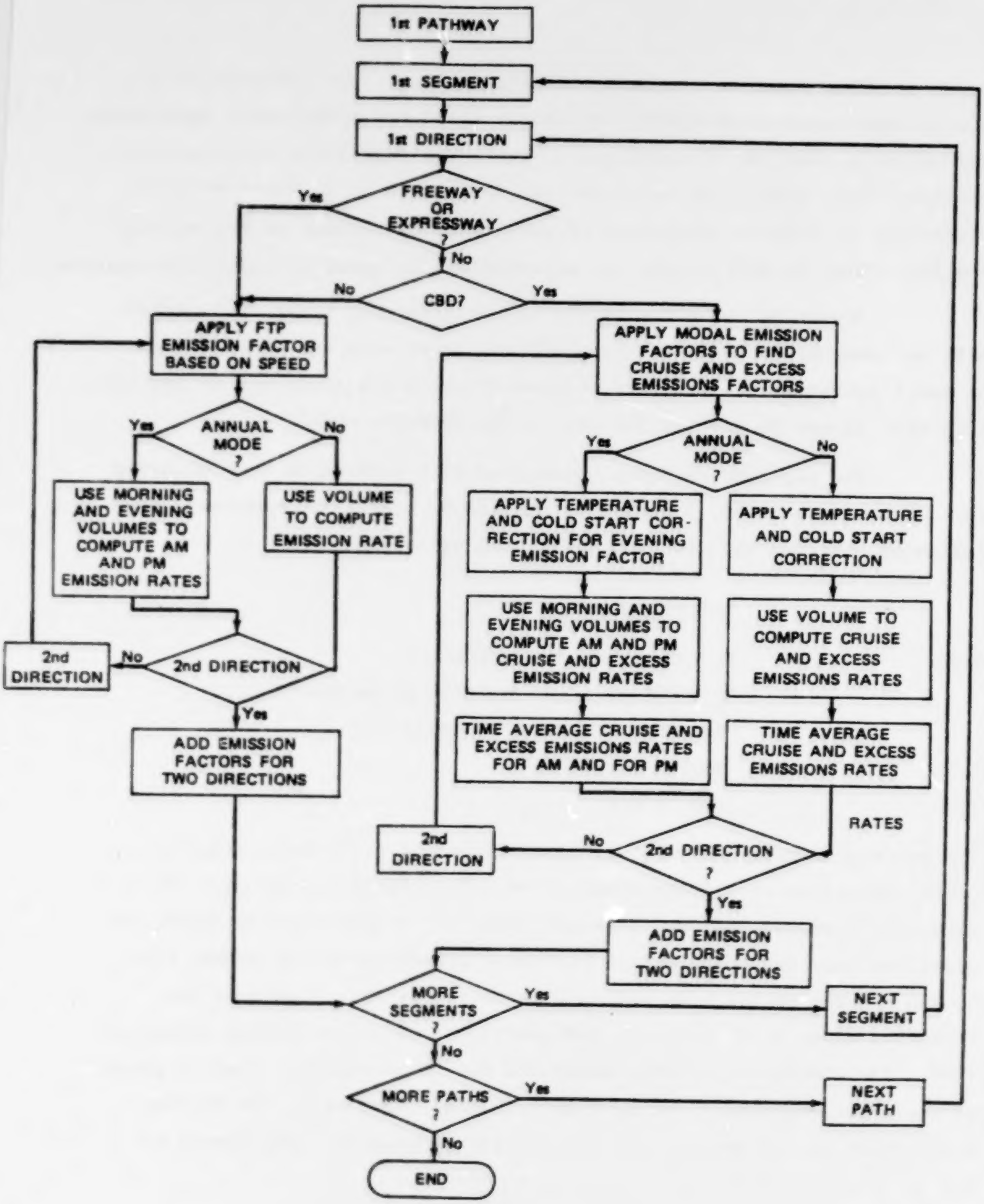

1st PATHWAY
1st SEGMENT
1st DIRECTION
FREEWAY OR EXPRESSWAY ?
Yes
No
CBD?
No
Yes
APPLY FTP EMISSION FACTOR BASED ON SPEED
APPLY MODAL EMISSION FACTORS TO FIND CRUISE AND EXCESS EMISSIONS FACTORS
ANNUAL MODE ?
Yes
No
USE MORNING AND EVENING VOLUMES TO COMPUTE AM AND PM EMISSION RATES
USE VOLUME TO COMPUTE EMISSION RATE
ANNUAL MODE ?
Yes
No
APPLY TEMPERATURE AND COLD START CORRECTION FOR EVENING EMISSION FACTOR
APPLY TEMPERATURE AND COLD START CORRECTION
USE MORNING AND EVENING VOLUMES TO COMPUTE AM AND PM CRUISE AND EXCESS EMISSION RATES
USE VOLUME TO COMPUTE CRUISE AND EXCESS EMISSIONS RATES
2nd DIRECTION
No
2nd DIRECTION
Yes
ADD EMISSION FACTORS FOR TWO DIRECTIONS
TIME AVERAGE CRUISE AND EXCESS EMISSIONS RATES FOR AM AND FOR PM
TIME AVERAGE CRUISE AND EXCESS EMISSIONS RATES
RATES
2nd DIRECTION
No
2nd DIRECTION ?
Yes
ADD EMISSION FACTORS FOR TWO DIRECTIONS
MORE SEGMENTS ?
Yes
NEXT SEGMENT
No
MORE PATHS ?
Yes
NEXT PATH
No
END

FIGURE 10. FLOWCHART OF PATHWAY EMISSION MODELING PROCEDURE

When there are no cold-starting vehicles, the combined cold-start-temperature-speed correction factor loses its temperature dependence and become a function of speed only. To reduce repetitive calculations, the model will compute emission factors for speeds of 10 to 60 mi/hr in increments of 5 mi/hr; estimates of speed will be rounded to the nearest 5 mi/hr. That is well within the accuracy of the speed estimation procedures.

Therefore, 11 FTP emission factors, corresponding to 11 speeds, will be computed for pathways for both the short-term and annual modes of model operation. A computer program of the FTP methodology is available from EPA; it can be adapted for use in the commuter model.

The mechanics of model operation will proceed in the following way. For each non-CBD, freeway, or expressway segment of a pathway, the following equation will be used to compute emissions:

$$Q = \frac{EV}{(3600)(1609)}$$

where Q = emissions rate, g/m/sec

E = FTP emission density, g/vehicle-mi.

V = demand volume, vehicles/hr

3600 = sec/hr

1609 = m/mi

The emission density, E, will be chosen from the previously computed table, according to average route speed. To compute the average emission rate over a segment having congested flow, it is convenient to break the emissions into two components: (1) those occurring during normal flow, E, and (2) the excess over normal flow emissions that occurs during congested flow, E'-E, where E' represents the emissions during congested flow. The component of total emissions due to uncongested flow is given by the above expression for Q, with E chosen according to the average route speed on the uncongested portion of the segment. The component due to congested flow is

$$Q' = \frac{(E'-E)\,\hat{N}}{1609\,\hat{T}}\ ,\ \text{g/m/sec}$$

where E' corresponds to an average route speed of 20 mi/hr and $\hat{T}$ is the duration (sec) of the backup. The average emission rate over the pathway segment is calculated as

$$Q_{avg} = Q + \frac{\hat{T}\ Lq\ Q'}{3600\ L}\ ,\ \text{g/m/sec}$$

where L = segment length, mi

Lq = backup length, mi

= 0.01 N.

Substituting for Q and Q' and reducing, the expression for Q_{avg} is

$$Q_{avg} = \frac{EV + (E'-E)\hat{N}\ Lq/L}{(1609)(3600)}\ .$$

In the annual mode, the model will compute two emission rates, using the volumes of the morning and evening commutes. In the short-term mode, the model will compute only one emission rate, appropriate to the volume of the hour during which the "average" commuter travels the segment.

Travel on arterials within the CBD is characterized by interrupted flow and low speeds, and a modal emissions treatment should be used. This is available through an adaptation of EPA's modal model.

The modal model determines an instantaneous emission rate, $\dot{e}(t)$, which is a function of vehicle speed, v, and acceleration, a. Since speed and acceleration are functions of time, the emission rate function can be expressed as

$$\dot{e}(t) = \dot{e}\left[v(t),\ a(t)\right]\ .$$

Acceleration to or from a given speed is assumed to be a perturbation to the steady-state emission rate, and two equations are used to describe the emission rate:

$$\dot{e}_A(v,a) = b_1 + b_2 v + b_3 a + b_4 av + b_5 v^2 + b_6 a^2 + b_7 av^2 + b_8 a^2 v + b_9 a^2 v^2 \quad \text{(A)}$$

and

$$\dot{e}_s(v,o) = b_{10} + b_{11} v + b_{12} v^2, \quad \text{(B)}$$

where the first equation describes the non-zero acceleration emission rate and the second describes emission rates for steady speeds. Note that the idle emission rate equals the coefficient b_{10}.

Inputs to the modal model include calendar year, vehicle model year mix for various locations (low or high altitude, California or outside California) and second-by-second speed data for the driving sequence being modeled. The two preceding equations are solved for each second, the results are taken as one-second integrated emissions, and the model output is the total emissions over the driving sequence. Eighteen vehicle groups can be included in the vehicle mix; deterioration as a function of calendar year is included in the emission calculations. The 18 groups are listed in Table 6.

Second-by-second speed profiles are inconvenient input data for roadway air-quality modeling. As a result, the basic modal model has been modified to accept and calculate more appropriate parameters. Patterson[8] modified the model to accept inital and target speeds and acceleration or deceleration as inputs, and to calculate an emission density (g/m) over successive eight-meter lengths of roadway. The distance of eight meters was chosen for convenience because it is the average distance occupied by a queued vehicle. Time was entered from traffic modeling data. Sandys[9] used the median speed during deceleration or acceleration as the basis for a modal emission calculation that was assumed to be an average value for the mode. Inputs were speed, and acceleration or deceleration. In other work, Patterson[10] computed emissions during acceleration and deceleration in a one-step process by integrating the instantaneous emission rate over time. That approach yields almost the same result as using the median speed, but it recognizes the nonlinear speed dependence of the fifth, seventh, and ninth terms of the instantaneous emission rate equations.

Modeling the effects of modal emissions is facilitated through the introduction of the concept of excess emissions. Excess emissions are those that occur over and above those that would have occurred had the vehicle not stopped. The acceleration or deceleration parts of excess emissions are then the difference between the acceleration or deceleration emissions given by equation (A) and the cruise emissions calculated by equation (B). Similarly, the idle part of excess emissions is the difference between the idle emissions, given by the coefficient b_{10} of equation (B), and the cruise emissions. The emissions during acceleration or deceleration

Table 6

VEHICLE GROUP DESIGNATIONS

Group 1 - 1957-1967 Denver

Group 2 - 1957-1967 low-altitude cities (non-California 1966, 1967)

Group 3 - 1966, 1967 California

Group 4 - 1968 low altitude cities (49-state)

Group 5 - 1969 low altitude cities (49-state)

Group 6 - 1970 low altitude cities (49-state)

Group 7 - 1971 low altitude cities (49-state)

Group 8 - 1968 Denver

Group 9 - 1969 Denver

Group 10 - 1970 Denver

Group 11 - 1971 Denver

Group 12 - 1972 Denver

Group 13 - 1973, 1974 Denver

Group 14 - 1972 California

Group 15 - 1973, 1974 California

Group 16 - 1972 low-altitude cities (49-state)

Group 17 - 1973, 1974 low-altitude cities (49-state)

Group 18 - 1975 low-altitude cities (49-state) are found by assuming that acceleration is constant, converting speed to a function of time, $v = at$, substituting in equation (A), and integrating over the time, T, to come to a stop or to reach cruise speed:

$$\text{Total acceleration or deceleratiom emissions} = \int_{o}^{T} \dot{e}_A(v(t),a)dt, \text{ grams.}$$

The cruise emissions that would have occurred had the vehicle not stopped are found by integrating $\dot{e}_s$ over ½ T:

$$\text{Cruise emissions} = \int_{o}^{T/2} \dot{e}_s(v(t),o)dt, \text{ grams.}$$

For one vehicle, the acceleration and deceleration parts of the excess emissions, E_{AD}, are, assuming acceleration equals deceleration:

$$E_{AD} = \int_{o}^{T} \dot{e}_A(v(t),a)dt + \int_{o}^{T} \dot{e}_A(v(t),-a)dt - 2 \int_{o}^{T/2} \dot{e}_s(v(t),o)dt$$

Idle emissions must be added to E_{AD} to arrive at the total excess emissions. The values for total excess emissions, E_E, in units of g/m/sec, are calculated as

$$E_E = \left(\frac{E_{AD} \; N}{Cy} + \frac{b_{10} D \; DVP}{3600} \right) /Lq \; .$$

The cruise emissions component may be calculated by

$$E_C = \frac{\dot{e}_s \; V/3600}{v \; 1609.344/3600} \text{ g/m/sec}$$

where 1609.344 is the number of meters in a mile. For calculating concentrations, note that the total excess emissions, E_E, will be averaged over the queue length. The cruise emissions component occurs at all points along the roadway.

Operationally, the values of E_{AD} will be calculated once and stored for inital and target speeds of 0 to 30 mi/hr in increments of 5 mi/hr. Acceleration and deceleration may be taken to be a constant 2.5 mi/hr/sec, based on work by Patterson[8] and Ludwig[2]. The inital speed for deceleration and the target speed for acceleration will generally be the same across an intersection. If the two speeds differ, the lower speed may be chosen to provide a conservative estimate when choosing a value for E_{AD} based on speed.

Once emissions are calculated with the modal treatment, they should be averaged for each link or pathway segment. To do this, the total excess emissions (excess per vehicle times the number stopping), E_E, are multiplied by the queue length, the cruise emissions are multiplied by the link length and the results are added and divided by the length of the link. This can be expressed as:

$$E_{avg} = \frac{E_E Lq + E_C x}{x}$$

where E_{avg} = average emissions on link, g/m/sec

Lq = queue length, mi

x = link length, mi

E_E = excess emissions per stopping vehicle, g/m/sec

E_c = cruise emissions per vehicle, g/m/sec.

The discussion on FTP emissions estimates mentioned the exclusion of cold-start (and therefore temperature) corrections, because vehicles were assumed to be warmed up on a freeway, expressway, and non-CBD arterial segments of the pathways. In the evening, vehicles leaving the CBD cannot be assumed to be warmed up, and correction factors must be applied to the emissions estimates. The EPA methodology for correcting modal emissions for cold-starts and temperature involves the use of the FTP combined speed-temperature-cold-start correction factors. A modal correction factor is found by taking the ratios of the FTP combined correction factors. The numerator of the ratio is the FTP correction factor computed for the temperature and percentages of cold-start, hot-start, and hot-transient vehicles of interest and the roadway's average route speed. The denominator of the ratio is the FTP correction factor for the the same temperature and average route speed, but with completely warmed-up vehicles. The commuter exposure model will compute this ratio for the input percentage of cold-starting vehicles. If the model is in the annual mode, the percentage of cold-starts will be for the evening commute in the CBD, and an annual average temperature for the evening commute period. If the model is in the short-term mode, the percentage refers to the single commute being analyzed, and the average temperature of that commute.

For both modes of operation, the correction factor will be computed for speeds from 0 to 30 mi/hr in increments of 5 mi/hr. Then, for each pathway segment, the correction factor for the appropriate average route speed will be used.

Another factor that must be considered for the modal model is a combined calendar-year/heavy-duty vehicle correction factor. The modal model is applicable to vehicles through 1975, and a correction must be made for later years. Also, because the modal methodology considers only light-duty vehicles, a factor that accounts for the vehicle type mix must be included. A correction factor to account for all of these considerations could be developed by: (1) making a number of computations for various conditions with the modal model using the future year deterioration factors; and (2) using the FTP methodology to compute ratios of composite emissions to light-duty vehicle emissions for various vehicle type mixes for different calendar years. A large number of computations would be involved, but similar factors have been developed with the use of the previously accepted FTP methodology. The correction factors developed in this way would be stored in the model and applied to estimates of modal emissions.

The user will have the option of inputing emission rates for each payment segment directly, and if that option is exercised, the emissions module described above will be bypassed. The direct input option may be particularly useful if a pollutant other than carbon monoxide is to be modeled.

2. Non-Pathway Emissions

Unless non-pathway emissions are input indirectly, emissions from primary and secondary traffic in the grid squares will be computed with the use of the latest FTP methodology. As mentioned under the discussion of pathway emissions, the methodology requires the following parameters:

- Calendar year
- Model year mix
- Vehicle type mix
- Average route speed
- Ambient temperature
- Percentage of cold-starting, hot-starting, and hot-transient vehicles.

The calendar year, the vehicle type mix, and the model year mix will be input and fixed over the time period over which exposures are to be computed (up to one year). For non-pathway emissions, the standard FTP average route speed of 19.6 mi/hr will be assumed in computing the combined speed-temperature-cold start correction factor. All other correction factors in the FTP methodology will be assumed to be unity for non-pathway sources.

When the commuter exposure model is in the annual mode, average annual morning and evening temperatures will be used in the combined correction factor. A table of percentages of cold-starting, hot-starting, and hot-transient vehicles, varying according to time of day (morning or evening), and locale type, will be stored in the model and used in computing the factors. The emissions module will be called once, and it will compute 10 emission factors: for the morning commute's temperature and five cold-start percentages (for the five locale types); and for the evening commute's temperature and five cold-start percentages. The model will enable the user to compute morning and evening emission rates for each grid square by: (1) choosing the emission factor appropriate to the time of day and the grid square's locale type, (2) multiplying the factor by the VMT of the grid square, (3) multiplying the total by the percentage of the daily VMT appropriate to the average hour of the commute, and (4) dividing the total by the area of the grid square.

When the model is in the short-term mode, the average temperature and cold-start percentages (for each of the five locale types) specific to the commute being analyzed will be input to the model. The emission module will compute an emission factor for each locale type, and the model will compute an emission rate for each grid square in the same manner as described previously for the annual mode of operation.

When daily gridded emissions are input directly, they must be converted to emission rates for the average commute hour. In the annual mode, percentages of daily traffic appropriate to the average morning and average evening commute hour will be applied to the daily rate for each square, in order to produce gridded morning and evening emissions. For the short-term mode, the percentage of daily traffic appropriate to the average hour of the commute being analyzed will be applied to each gridded emission rate.

E. Dispersion Modeling

1. Dispersion of Pathway Emissions

a. Limited-Access Roadways

To compute the dispersion of pollutants from limited-access roadways, a semi-empirical approach will be followed, patterned after the ROADMAP model of Dabberdt.[11] The model formulation is based on the treatment of pollution dispersion as the vector sum of two components: (1) dispersion occurring along the horizontal wind component oriented perpendicular to the roadway; and (2) dispersion along the horizontal wind component parallel to the roadway. It is assumed that there is no vertical transport by a non-zero mean vertical wind component. Figure 11 illustrates the coordinate system for a one-way road.

The two-component dispersion formulation can be written as:

$$\frac{X_T U}{Q_1} = \frac{\vec{i} X_n u}{Q_1} + \frac{\vec{j} X_p v}{Q_1}$$

where $\vec{i}$ = unit vector normal to roadway
$\vec{j}$ = unit vector parallel to roadway
U = vector wind speed (m/sec)
u = wind component normal to roadway (m/sec)
v = wind component parallel to roadway (m/sec)
Q_1 = line source emission rate (g/m-sec)
X_T = total pollutant concentration (g/m^3)
X_n = concentration from lateral dispersion (g/m^3)
X_p = concentration from longitudinal dispersion (g/m^3).

When θ is introduced as the angle between the longitudinal axis of the line source and the wind vector, then

$$u = U \sin \theta, \text{ and}$$
$$v = U \cos \theta.$$

Substituting and squaring both sides,

$$\left[\frac{X_T U}{Q_1}\right]^2 = \left[\frac{X_n U \sin \theta}{Q_1}\right]^2 + \left[\frac{X_p U \cos \theta}{Q_1}\right]^2$$

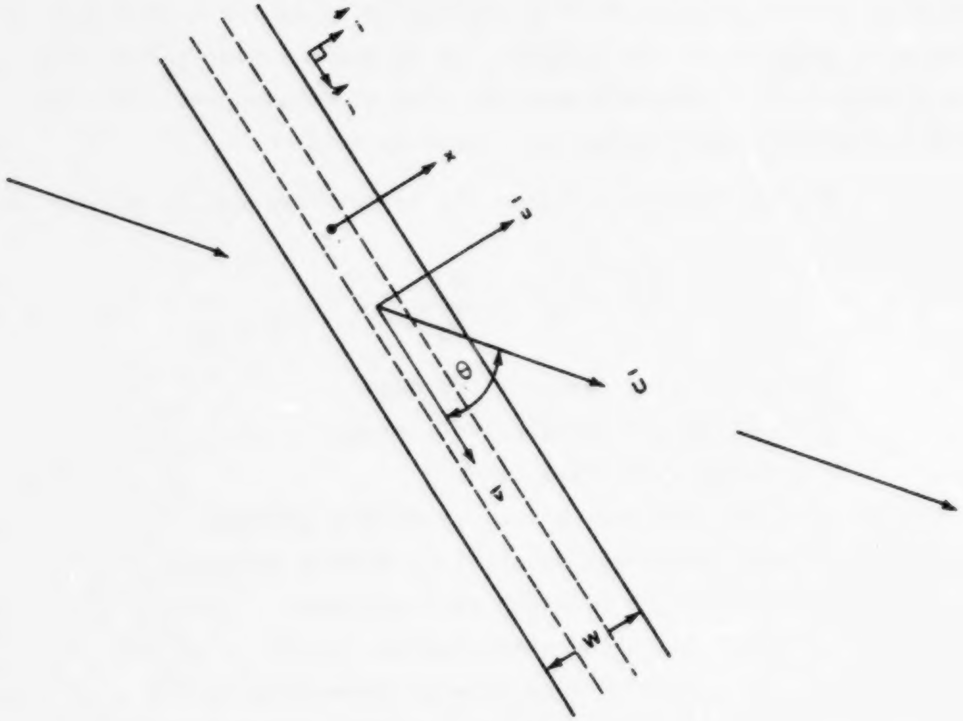

$\bar{i}$
$\bar{j}$
x
$\bar{u}$
Θ
$\bar{U}$
$\bar{v}$
W

FIGURE 11. ILLUSTRATION OF A LIMITED–ACCESS ROADWAY SEGMENT SHOWING PARAMETERS USED IN DISPERSION COMPUTATIONS

For convenience, the first right-hand term in the above equation is designated the "perpendicular" term and the second, the "parallel" term.

The form of the perpendicular term is specified in analogy to the Gaussian line source equation for a perpendicular wind,

$$\left[\frac{X_n U}{Q_1}\right] = \frac{\sqrt{2/\pi}}{\sigma_z}\left\{\exp\left[\frac{-1}{2}\left(\frac{z + z'}{\sigma_z}\right)^2\right]\right)$$

where σ_z = vertical Gaussian dispersion function (m)

z = height of the receptor above grade-level (m)

z' = height offset from plume rise (m).

The term z' serves as a height-modifier to represent the possible change in the height of the plume centerline as a function of distance downwind. This offset could result either from the aerodynamic influence (i.e. shelterbelt) of the traffic stream or from the buoyancy effect of vehicular waste heat emissions.

The parallel dispersion term was formulated to represent the general features of the Gaussian point source equation when the latter is integrated for a wind aligned parallel to a semi-infinite line source. The resulting formulation may be thought of as a type of expanding-box model whose sides and top are given as exponential functions of height (z) and cross-roadway distance (x). The form chosen assumes the same functional dependence on height as the perpendicular term, but a different cross-roadway dispersion representation (f).

$$\left[\frac{X_p U}{Q_1}\right] = \frac{1}{\sigma_{z-o} f}\left\{\exp\left[-\frac{1}{2}\left(\frac{z + z'}{\sigma_z}\right)^2\right]\right)$$

where

$$\sigma_z = \sigma_{z-o} + a_1 x^{b_1} ,$$

$$z' = z'_o + a_2 x^{b_2} ,$$

$$f = a_3 (c_3 + \frac{2x}{W})^{b_3}$$

and W = roadway width (m).

The parameters that this dispersion treatment will require, either as model input, or from the traffic and emissions portions of the model, are the pathway segment emission rate, roadway width, wind speed, wind direction, and atmospheric stability. All other parameters in the dispersion formulation can be incorporated in the model of the preceding variables, those that vary with time are emissions, wind direction, wind speed, and stability. Concentration can easily be normalized with respect to wind speed. Thus, wind-speed-normalized concentrations on limited-access roadways will be a function of emissions, wind direction, and stability.

b. Non Limited-Access Roadways

The dispersion of pollutants emitted by vehicles on non-limited-access roadways will be computed by a technique taken from the CALINE 2[12] model. The technique is similar to the limited-access roadway dispersion treatment described in the previous subsection, but is more suitable for modeling dispersion on non-limited access roadways because it does not include terms (that are in ROADMAP) that describe the enhanced vehicle waste heat emissions, mechanically induced turbulence, or the "shelterbelt" effect present on freeways. Because of these terms, it is doubtful that ROADMAP could accurately predict concentrations at locations where low speed driving controlled with signals is practiced. The concentration is separated into cross-wind and parallel wind components. The major difference in the formulations is in the consideration of the parallel wind components. The parallel wind model in CALINE 2 assumes that the roadway is divided into a series of square area sources as wide as the roadway. The concentration downwind of the area source is computed as if the emissions originated from a virtual source upwind of the area source. The distance from the center of the area source to the virtual source is set so that the model is forced to assume a uniform concentration within a mixing cell over the roadway.

The equation used to compute the normalized concentration from each area source is:

$$\frac{X_p U}{Q_\ell} = \frac{\sqrt{\frac{2}{\pi}}\, W \cos^2\theta}{\sigma_y\, \sigma_z} \left\{ \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2\right] \right\}$$

where X_p = concentration from parallel dispersion (g/m^3)

U = wind speed (m/sec)

Q_ℓ = line source emission rate (g/m/sec)

W = roadway width (m)

θ = angle between wind direction and roadway

y = perpendicular distance between receptor and roadway edge plus an initial dispersion parameter (m)

z = height of the receptor above grade-level (m)

σ_y = horizontal dispersion function (m)

σ_z = vertical dispersion function (m).

The number of area sources used is equal to one-half mile divided by the width of the roadway. The concentrations from each area source are summed to give the parallel component, which, in CALINE 2, is then corrected by a stability-dependent factor that increases the line source length to five miles. Correction factors for roadways of different lengths will be derived and incorporated in the commuter exposure model.

The cross-wind or normal component of concentration is given by:

$$\frac{X_n U}{Q_\ell} = \frac{\sqrt{\frac{2}{\pi}}\, \sin^2\theta}{\sigma_z} \left\{ \exp\left[-\frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2\right] \right\}$$

where X_n = concentration from normal dispersion (g/m^3).

The parallel and crosswind components are summed to give the total concentration when θ is non -zero.

As in the dispersion treatment for limited-access roadways, wind speed normalized concentration will be a function of emissions, wind direction, and stability.

A note should be made here concerning the use of CALINE2 for computation of dispersion on non-limited access roadways. It appears that a further update of the model, to be called CALINE3, will soon be released. This model should be examined for its potential applicability to the commuter exposure model.

One of the problems encountered with virtually all existing dispersion models is that they do not predict concentrations on the roadway. The ROADMAP and CALINE2 models were chosen for this application because they can predict the concentration at the edge of the roadway or in a mixed cell over the roadway. The effects of this limitation should be examined using actual data gathered in a field program designed to study this problem.

c. Street Canyons

Dispersion on a roadway with tall buildings on both sides is greatly influenced by the presence of the buildings. The street-canyon dispersion treatment to be used in the commuter exposure model is based on the empirical street-canyon model developed by Johnson et al.[13] and modified by Ludwig et al.[14]. Their studies give evidence of a helical air circulation in street canyons, as illustrated in Figure 12. The concentration arising from street-canyon emissions on the leeward side of buildings is given by:

$$X_\ell = \frac{KQ_\ell}{\left(U+0.5\right)\left[\left(x^2+z^2\right)^{1/2}+L_0\right]} .$$

where

X_{ℓ} = concentration on leeward side of street (g/m^3)

Q_{ℓ} = line source emission rate (g/m/sec)

K = empirically derived nondimensional constant ≃ 7

U = wind speed (m/sec)

x and z = horizontal and vertical distance of the receptor relative to the center of the traffic lane (m)

L_o = dimension representing vehicle size ≃ 2 m.

The concentration on the windward side of the street is given by:

$$X_w = \frac{KQ_{\ell}\ (H-z)}{W(U+0.5)H}$$

where

X_w = concentration on windward side of street (g/m^3)

H = average building height (m)

W = street width (m).

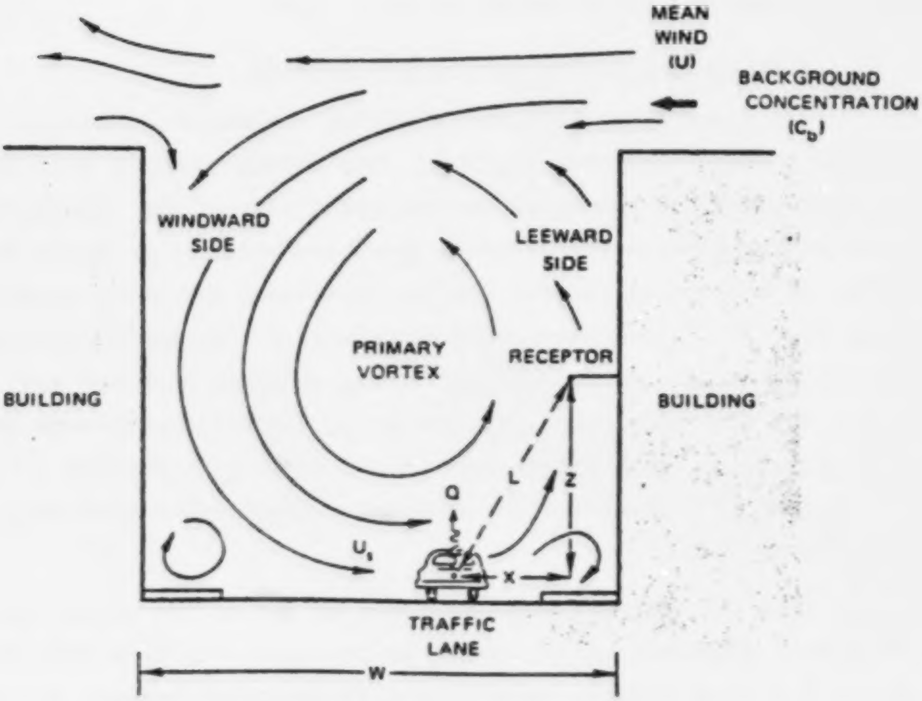

MEAN
WIND
(U)
BACKGROUND
CONCENTRATION
(C_b)
WINDWARD
SIDE
LEEWARD
SIDE
PRIMARY
VORTEX
RECEPTOR
BUILDING
BUILDING
Q
L
Z
U_s
X
TRAFFIC
LANE
W

FIGURE 12 SCHEMATIC OF CROSS-STREET CIRCULATION BETWEEN BUILDINGS

In the commuter exposure model, the concentration on the roadway will be assumed to be the average of the concentration on the windward and leeward sides of the street. Since the receptor is on the roadway, x and z are zero.

Substituting, and combining the above equations gives:

$$X = \frac{1}{2}\left[\frac{KQ_\ell}{(U+0.5)L_o} + \frac{KQ_\ell}{W(U+0.5)}\right]$$

$$= \frac{KQ_\ell}{2(U+0.5)}\left(\frac{1}{L_o} + \frac{1}{W}\right).$$

Since W is usually considerably larger than L_o, the 1/W term is small in comparison with the $1/L_o$ term. Considering this, the concentration relationship resembles that of a box model.

Thus, concentrations in street canyons are described by the time dependent parameters of emissions and wind speed.

d. Computation of Concentration Statistics

The three dispersion methodologies discussed previously will be used to compute exposures resulting from pathway sources when the commuter exposure model is run in either the short-term or the annual mode. The differences in the mechanics of model operation between the modes are: (1) the number of meteorological and traffic conditions for which exposures are computed; and (2) the treatment of a commute as a time period with fixed meteorology and emissions, or as a period during which meteorology and emission rates may vary with time. The following discussion explains the mechanics of dispersion computations for the two modes of operation. The flowchart in Figure 13 illustrates the dispersion computation procedure for pathway sources.

When the commuter exposure model is run in the short-term mode, it will make computations of concentrations resulting from pathway sources in the following manner. Beginning with the first segment of the

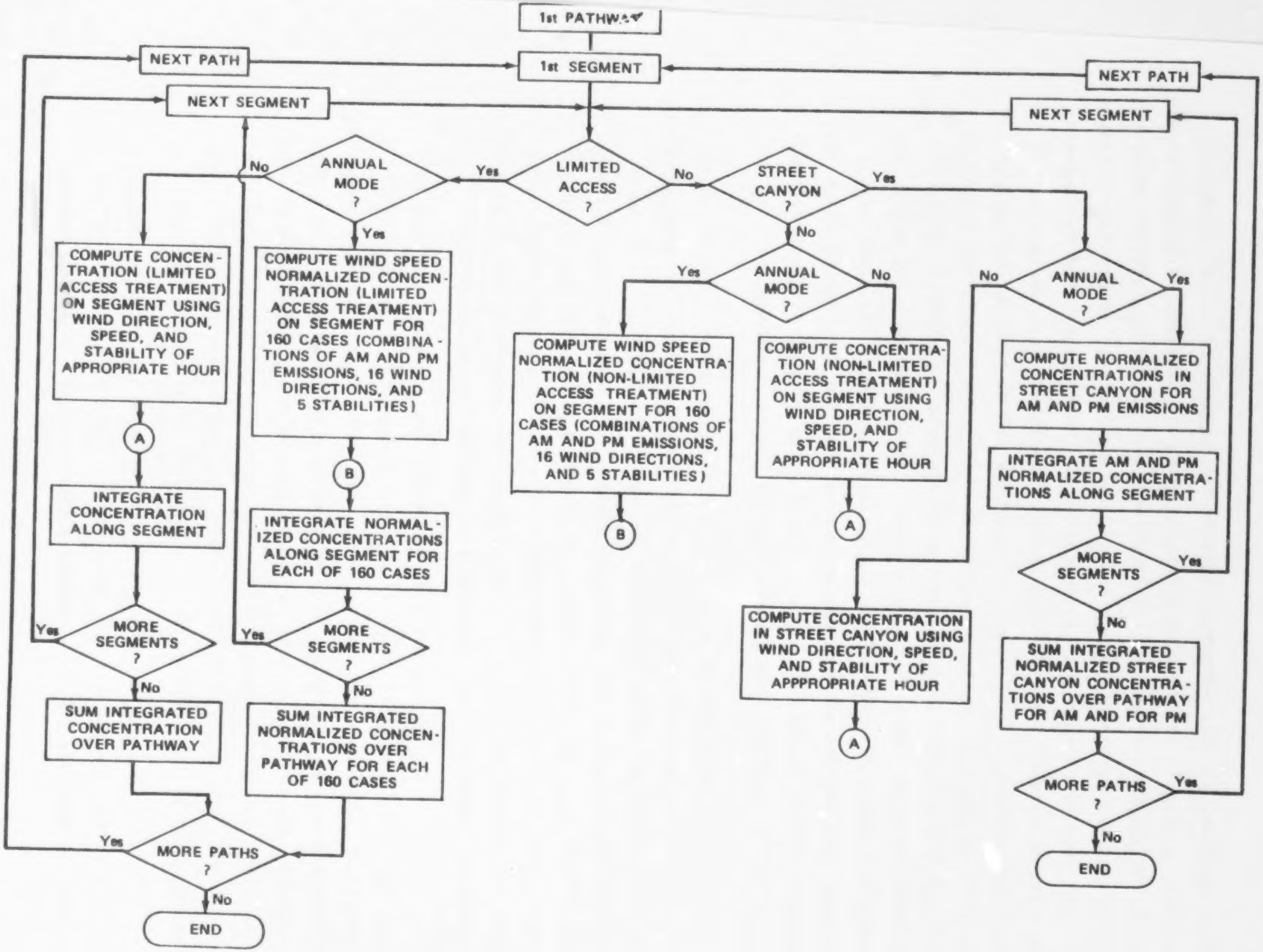

1st PATHWAY
NEXT PATH
1st SEGMENT
NEXT PATH
NEXT SEGMENT
NEXT SEGMENT
LIMITED ACCESS ?
Yes
No
ANNUAL MODE ?
No
Yes
STREET CANYON ?
Yes
No
COMPUTE CONCENTRATION (LIMITED ACCESS TREATMENT) ON SEGMENT USING WIND DIRECTION, SPEED, AND STABILITY OF APPROPRIATE HOUR
A
INTEGRATE CONCENTRATION ALONG SEGMENT
MORE SEGMENTS ?
Yes
No
SUM INTEGRATED CONCENTRATION OVER PATHWAY
COMPUTE WIND SPEED NORMALIZED CONCENTRATION (LIMITED ACCESS TREATMENT) ON SEGMENT FOR 160 CASES (COMBINATIONS OF AM AND PM EMISSIONS, 16 WIND DIRECTIONS, AND 5 STABILITIES)
B
INTEGRATE NORMALIZED CONCENTRATIONS ALONG SEGMENT FOR EACH OF 160 CASES
MORE SEGMENTS ?
Yes
No
SUM INTEGRATED NORMALIZED CONCENTRATIONS OVER PATHWAY FOR EACH OF 160 CASES
MORE PATHS ?
Yes
No
END
ANNUAL MODE ?
Yes
No
COMPUTE WIND SPEED NORMALIZED CONCENTRATION (NON-LIMITED ACCESS TREATMENT) ON SEGMENT FOR 160 CASES (COMBINATIONS OF AM AND PM EMISSIONS, 16 WIND DIRECTIONS, AND 5 STABILITIES)
B
COMPUTE CONCENTRATION (NON-LIMITED ACCESS TREATMENT) ON SEGMENT USING WIND DIRECTION, SPEED, AND STABILITY OF APPROPRIATE HOUR
A
ANNUAL MODE ?
No
Yes
COMPUTE CONCENTRATION IN STREET CANYON USING WIND DIRECTION, SPEED, AND STABILITY OF APPPROPRIATE HOUR
A
COMPUTE NORMALIZED CONCENTRATIONS IN STREET CANYON FOR AM AND PM EMISSIONS
INTEGRATE AM AND PM NORMALIZED CONCENTRATIONS ALONG SEGMENT
MORE SEGMENTS ?
Yes
No
SUM INTEGRATED NORMALIZED STREET CANYON CONCENTRATIONS OVER PATHWAY FOR AM AND FOR PM
MORE PATHS ?
Yes
No
END

FIGURE 13. FLOWCHART OF PATHWAY DISPERSION COMPUTATION PROCEDURE

first pathway, it will determine whether the segment is a limited-access roadway, a street canyon, or a non-street-canyon, non-limited-access roadway. Using the input wind speed, wind direction, and stability, and the emission rate generated by the emissions module, the appropriate dispersion treatment will be used to compute the concentration on the segment. (If the segment is a street canyon, only the wind speed and emission rate are required.) Then, the concentration is multiplied by the travel time on the segment to yield an exposure on the segment. The model will repeat the procedure for each segment of a pathway and sum the segment exposures to produce a pathway exposure. When each new segment of a pathway is encountered, the model will check the travel time on the pathway before the start of the segment, and use the meteorology appropriate to the hour during which the segment will be traveled. The model will cycle through all pathways and calculate an exposure from pathway sources for each pathway.

When the model is run in the annual mode, it will attempt to produce exposure statistics representative of the various meteorological conditions and emissions that occur during a typical year. If a model individually computed the morning and evening computer exposures for each day of the year, for several years, to ensure a representative "average" year's statistics, a very large number of computations would need to be made, at considerable cost. To avoid that, the numerical model is designed to compute exposures only once for each combination of conditions.

The parameters that determine the concentration and vary with time are wind speed, wind direction, atmospheric stability, and emissions. Concentration can be normalized with respect to wind speed (in the street-canyon treatment, with respect to wind speed plus 0.5). Thus, separate computations need be made only for various combinations of wind direction, stability, and emissions. Let wind direction be divided into 16 classes, stability into five classes, and emissions into morning and evening values. All combinations of those classes make up 160 cases.

Morning and evening emission rates and travel times will be passed from the traffic and emissions portions of the model to the dispersion portion. It will compute exposure in the following manner.

As in the short-term mode, it will begin with the first segment of the first pathway and determine the segment's roadway type. If the roadway type is limited-access or non limited-access and not a street canyon, the appropriate dispersion treatment (of the preceding two) will be used to compute wind-speed-normalized concentrations on the segment for each of the 160 cases. If the segment is a street canyon, there is no dependence on wind direction or stability, so normalized concentrations will be computed for two cases: morning and evening emissions. Once the set of normalized concentrations is computed, each concentration will be multiplied by the appropriate travel time on the segment (morning or evening) to produce a set of exposures on the segment. The model will repeat the procedure for each segment of a pathway and sum exposures from all non-street canyon segments of the pathway for each of the 160 cases. Two other sums will be created for the pathway: the sums of exposures on street-canyon segments for morning and evening commutes. Those exposures must be stored separately because they are normalized by wind speed plus 0.5, instead of just wind speed, as on the non-street-canyon segments. The model will cycle through all pathways and produce a set of exposures from pathway sources for each pathway. The 162 values for each pathway (160 exposures for non-street-canyon parts of the pathway plus the values for the two street-canyon exposures), along with the 10 exposure values for each pathway resulting from non-pathway sources (described in the next section) will be used to develop the annual commuter exposure statistics.

2. Dispersion of Non-Pathway Source Emissions

It is expected that the portion of the total pathway integrated concentration (exposure) that results from non-pathway sources will be small in comparison to the portion resulting from traffic on the commuter pathways themselves. Therefore, a very simple emissions and dispersion treatment will be used, both to reduce computational time on the computer and to simplify the data required to be input by the user.

The line-source emissions on non-pathways have been aggregated into area source emissions from grid squares, according to the methodology previously presented. The approach to be used to compute the concentrations along the commuter pathways resulting from the area source emissions is the so-called Hanna-Gifford[15] dispersion treatment. The basic assumption of the treatment is that the area source strength in a metropolitan area varies by less than a factor of 10 over distances of a few kilometers. That assumption permits the horizontal cross-wind dispersion component to be neglected in comparison with the vertical component. If the area sources are a gridded system, with grid spacing of one to 10 km, the concentration in grid 0 can be calculated according to the formula:

$$X = \sqrt{\frac{2}{\pi}}\,\frac{(\Delta x/2)^{1-b}}{Ua(1-b)}\left\{Q_o + \sum_{i=1}^{N} Q_i\,\left[(2i+1)^{1-b} - (2i-1)^{1-b}\right]\right\}$$

where X = concentration in grid 0

Q = emission rate

U = wind speed

Δx = grid spacing

N = number of upwind grid squares

a,b = constants, dependent on stability

and the subscript i refers to the upwind grid squares, with zero denoting the central square, 1 denoting the square next upwind, and so forth.

The equation can be simplified by taking advantage of the fact that the influence on X_o of source areas far upwind from the central area is small due to the rapid decrease of terms multiplying Q_i as i increases. Making the assumption that $Q_i \approx Q_o$, the equation can be approximated in the following manner:

$$X = \frac{CQ_o}{U}$$

where

$$C = \sqrt{\frac{2}{\pi}}\,\frac{D^{1-b}}{a(1-b)}$$

and D = city size. The values of a and b for various stability regimes are shown in Table 7.

Table 7

VALUES OF THE CONSTANTS a AND b FOR VARIOUS STABILITIES

Stability	a	b
Very unstable	0.40	0.91
Unstable	0.33	0.86
Neutral	0.22	0.80
Estimated Pasquill's "D" (average)	0.15	0.75
Stable	0.06	0.71

Thus, for any point on a pathway, the approximated form of the equation can be used to compute the concentration from area sources. The commuter model will compute those concentrations on a pathway-by-pathway basis. For a given pathway, the model will take the first segment and determine which grid squares contain the segment end points. The coordinates of the midpoint of the segment will be generated, and the grid square in which the midpoint is located will be determined. For each of these grid squares, a concentration normalized by wind speed will be calculated according to the relationship discussed above. Concentrations would be calculated, for example, for the point P_1, P_2 (the midpoint), and point P_3 in Figure 14. The traffic model will have generated the times at which the average vehicle reaches P_1, P_2, and P_3. From them, two travel times can be derived: (1) the travel time from P_1 to P_2, called T_1, and (2) the travel time from P_2 to P_3, called T_2. Thus,

$$T_1 = t_2 - t_1 \text{ and } T_2 = t_3 - t_2.$$

The normalized integrated concentration over the segment (the exposure) is given by:

$$\frac{E}{U} = \int_{t_1}^{t_3} \frac{X}{U}\, dt.$$

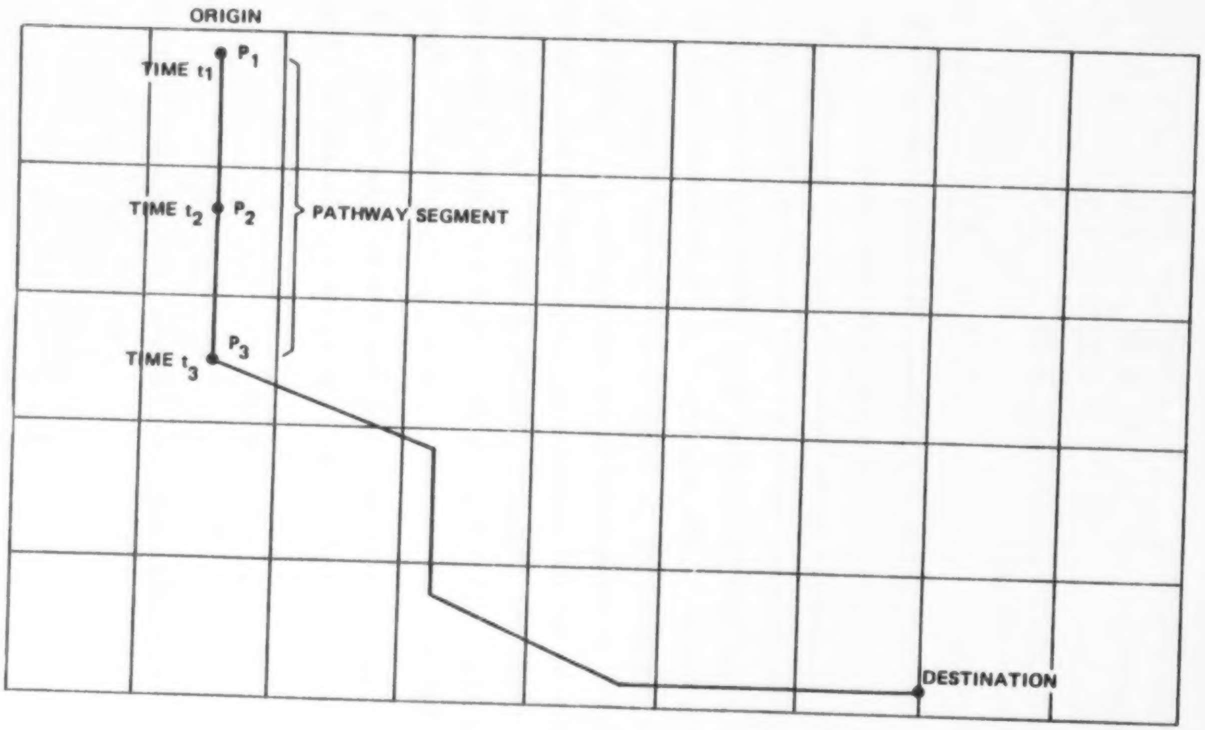

ORIGIN
TIME t_1
P_1
TIME t_2
P_2
PATHWAY SEGMENT
TIME t_3
P_3
DESTINATION

FIGURE 14. ILLUSTRATION OF INTEGRATION TECHNIQUE FOR NON–PATHWAY CONCENTRATIONS

Through a stepwise integration, the following relationship results:

$$\frac{E}{U} = \int_{t_1}^{t_2} \frac{X}{U}\,dt + \int_{t_1}^{t_3} \frac{X}{U}\,dt$$

$$= \left(\frac{X_1 + X_2}{2}\right)\frac{T_1}{U} + \left(\frac{X_2 + X_3}{2}\right)\frac{T_2}{U}$$

$$= \frac{1}{2}\left\{\frac{X_1}{U}T_1 + \frac{X_2}{U}(T_1 + T_2) + \frac{X_3}{U}T_2\right\}.$$

This normalized exposure applies to only one segment of a pathway. The model will compute similar exposures for all segments of a pathway, and sum the results to yield the normalized pathway exposure resulting from non-pathway sources.

When the model is in the annual mode, wind-normalized exposures on all pathways will be computed for five stability classes and two times of day (morning and evening). Thus, 10 exposure values will be stored for each pathway for use in developing the statistics that will describe commuter exposure.

When the model is in the short-term mode, the exposure on each pathway for the input wind speed and stability will be computed using the model-generated emission rate.

Figure 15 is a flowchart showing the treatment of traffic, emissions and dispersion from non-pathway sources.

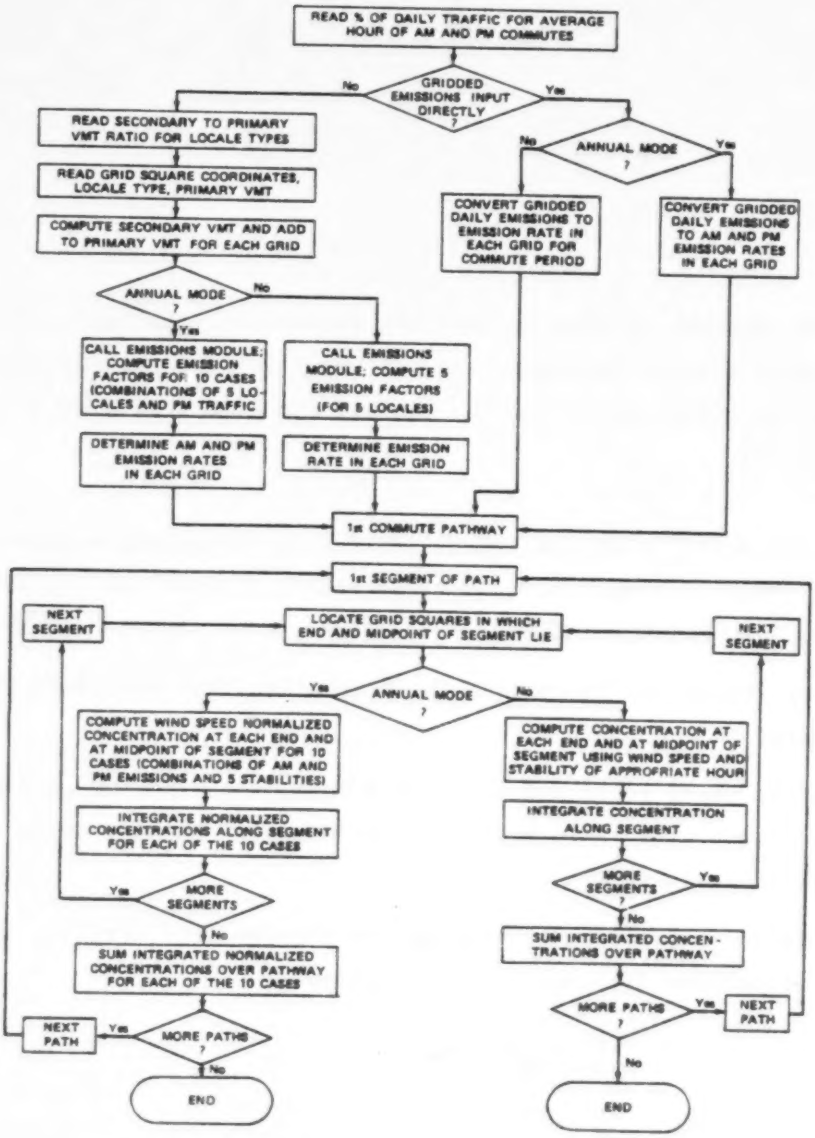

READ % OF DAILY TRAFFIC FOR AVERAGE HOUR OF AM AND PM COMMUTES
GRIDDED EMISSIONS INPUT DIRECTLY ?
No
Yes
READ SECONDARY TO PRIMARY VMT RATIO FOR LOCALE TYPES
READ GRID SQUARE COORDINATES, LOCALE TYPE, PRIMARY VMT
COMPUTE SECONDARY VMT AND ADD TO PRIMARY VMT FOR EACH GRID
ANNUAL MODE ?
No
Yes
CONVERT GRIDDED DAILY EMISSIONS TO EMISSION RATE IN EACH GRID FOR COMMUTE PERIOD
CONVERT GRIDDED DAILY EMISSIONS TO AM AND PM EMISSION RATES IN EACH GRID
ANNUAL MODE ?
No
Yes
CALL EMISSIONS MODULE; COMPUTE EMISSION FACTORS FOR 10 CASES (COMBINATIONS OF 5 LOCALES AND PM TRAFFIC
CALL EMISSIONS MODULE; COMPUTE 5 EMISSION FACTORS (FOR 5 LOCALES)
DETERMINE AM AND PM EMISSION RATES IN EACH GRID
DETERMINE EMISSION RATE IN EACH GRID
1st COMMUTE PATHWAY
1st SEGMENT OF PATH
NEXT SEGMENT
LOCATE GRID SQUARES IN WHICH END AND MIDPOINT OF SEGMENT LIE
NEXT SEGMENT
ANNUAL MODE ?
Yes
No
COMPUTE WIND SPEED NORMALIZED CONCENTRATION AT EACH END AND AT MIDPOINT OF SEGMENT FOR 10 CASES (COMBINATIONS OF AM AND PM EMISSIONS AND 5 STABILITIES)
COMPUTE CONCENTRATION AT EACH END AND AT MIDPOINT OF SEGMENT USING WIND SPEED AND STABILITY OF APPROPRIATE HOUR
INTEGRATE NORMALIZED CONCENTRATIONS ALONG SEGMENT FOR EACH OF THE 10 CASES
INTEGRATE CONCENTRATION ALONG SEGMENT
MORE SEGMENTS
Yes
No
MORE SEGMENTS ?
Yes
No
SUM INTEGRATED NORMALIZED CONCENTRATIONS OVER PATHWAY FOR EACH OF THE 10 CASES
SUM INTEGRATED CONCENTRATIONS OVER PATHWAY
NEXT PATH
Yes
MORE PATHS ?
No
END
MORE PATHS ?
Yes
NEXT PATH
No
END

FIGURE 15. FLOW CHART OF NON-PATHWAY SOURCE TRAFFIC, EMISSIONS, AND DISPERSION COMPUTATION PROCEDURE

3. On-Roadway/In-Vehicle Concentration Relationship

A search of the literature has yielded a limited amount of information about the relationship between the concentration on the roadway and the concentration within a vehicle. Several papers[16, 17, 18] discuss in-vehicle concentrations, but only two references[19, 20] could be found that presented measurements of concentrations both inside and outside a vehicle. In one study[19] the pollutants measured were O_3, CO, NO, and NO_x; measurements were made on only one vehicle with the windows closed and the air conditioner set on maximum or normal for most of the time. The study concluded that concentrations of CO, NO, and NO_x inside a vehicle are about equal to that on the outside, while the O_3 inside concentration was a factor of 3 or 4 lower than the outside concentration, due to decay of O_3 on the surfaces within the vehicle. The other study[20] discussed measurements of particulate lead; levels inside the vehicle were approximately three-quarters of the levels outside the vehicle.

Therefore, since so little work has been directed toward establishing a data base suitable for deriving on-roadway/in-vehicle relationships, both the numerical and manual commuter exposure models will assume the concentrations at the two locations are identical. The commuter model will be of most use in predicting carbon monoxide exposure, and one of the studies discussed above found inside and outside CO concentrations to be about equal.

Even if the assumption is made that all of the pollutant outside the vehicle will find its way inside the vehicle, a question still remains concerning the time response of the inside concentration with respect to changes in the outside concentration. Evidently, the response is very rapid, since both concentrations have been found to be approximately the same. Further reinforcement to this theory is given by Chaney,[18] who measured concentrations within a vehicle with the windows closed and the fan on maximum. He often found a distinct increase in CO concentration when his vehicle was passed by another vehicle. The increase occurred a few seconds after the passage of the vehicle.

When a good body of data becomes available, on-roadway/in-vehicle concentration relationships will be able to be established. They will most likely depend on the state of the windows (closed or open), the state of the fan, air conditioner and heater, the vehicle model, and whether there is smoking occurring in the vehicle. It appears that for CO, inside and outside concentrations will be similar. However, it is expected that in some vehicles, with the windows closed and no ventilation system in operation, inside concentrations, while responding to perturbations in outside concentrations, in effect will be filtered.

If on-roadway/in-vehicle concentration relationships were available, and assuming the correction factor would be directly proportioned to concentration, application of the relationships could be made in one of two places in the model. If the relationships were a function of model year, they would need to be applied in the emissions module, before the individual emission factors for each model year are weighted by the fraction of travel for each model year. If the relationships were not model year dependent, they could be applied after concentrations have been calculated, but before exposure statistics are tabulated.

F. Commuter Exposure Statistics

The exposures to be computed for each pathway for each mode of model operation were discussed in the previous sections. In addition to the exposures, the model will store the total travel time or times on each pathway and the average number of commuters using the pathway. The commuter exposure statistics to be developed by the model from the previously computed values and the manner in which the model will compute those statistics for each mode of model operation are outlined in the following paragraphs.

1. Short-term Statistics

When the model is run in the short-term mode, commuter exposures will be output in three forms. One type of output is a list of the exposure on each pathway for the input worst-case meteorological and traffic conditions and the average and standard deviation of pathway exposure. The other two outputs are data that can be used to construct a histogram. The range of exposures found on all pathways will be divided into several classes. For each class two parameters will be listed: (1) the percentage of the commuting population (commuting vehicles mutiplied by the average number of commuters per vehicle) treated by the model that experience exposure levels in the class; and (2) the probability of experiencing the exposure levels in the class (i.e., the percentage of time commuters are exposed to the levels of the exposure class).

The first form of output will be found by simply adding the exposures on each pathway resulting from pathway and from non-pathway sources, listing the results, and taking the average and standard deviation of the values. These numbers will describe the spatial variation of exposures. The histogram data will be produced by: (1) assigning a range of exposure values to be included in each exposure class; (2) determining in which class the total exposure value on each pathway lies and assigning the pathway's commuters and travel time multiplied by commuters (commuter minutes) to that class; and (3) tabulating the number of commuters and the commuter-weighted travel times in each class.

Dividing the number of commuters associated with each class by the total number of commuters on the pathway network yields the percentage of commuters exposed to each range of exposure values. Dividing the commuter-minutes associated with each class by the total commuter-minutes on the pathway network gives the probability of occurrence of the exposure levels in each class.

2. Annual Statistics

Two forms of annual statistics from which histograms can be made will be produced by the model when it is in the annual mode. In addition, subsets of those statistics may be output at the user's discretion. The two kinds of annual histogram data that will be generated are: (1) the percentage of commuters exposed to various classes (ranges) of exposure; and (2) the probability of experiencing various classes of exposure (i.e., the percentage of time commuters are exposed to various classes of exposure).

The manner in which the model will produce both of those types of statistics is illustrated graphically in Figure 16. The model will begin with the first pathway. As stated previously, several normalized exposure will have been computed for each pathway: 160 normalized exposures arising from non-street-canyon pathway sources (for 16 wind directions, five stabilities, and morning and evening emission rates); two normalized exposures resulting from street-canyon sources (for morning and evening emission rates); and ten normalized exposures resulting from non-pathway sources (for five stabilities, and morning and evening emission rates). The model will take the first of the 160 cases (one combination of wind direction, stability, and morning or evening emissions) and multiply the exposure by one of six wind speed values. Next, the normalized street-canyon exposure for the corresponding time (morning or evening) will be multiplied by the same wind speed plus 0.5. Finally, the normalized non-pathway source exposure for the corresponding time and stability will be multiplied by the wind speed, and all three exposure values will be summed. The model will determine the exposure class in which this total exposure value lies, and it will multiply the pathway travel time by the number of

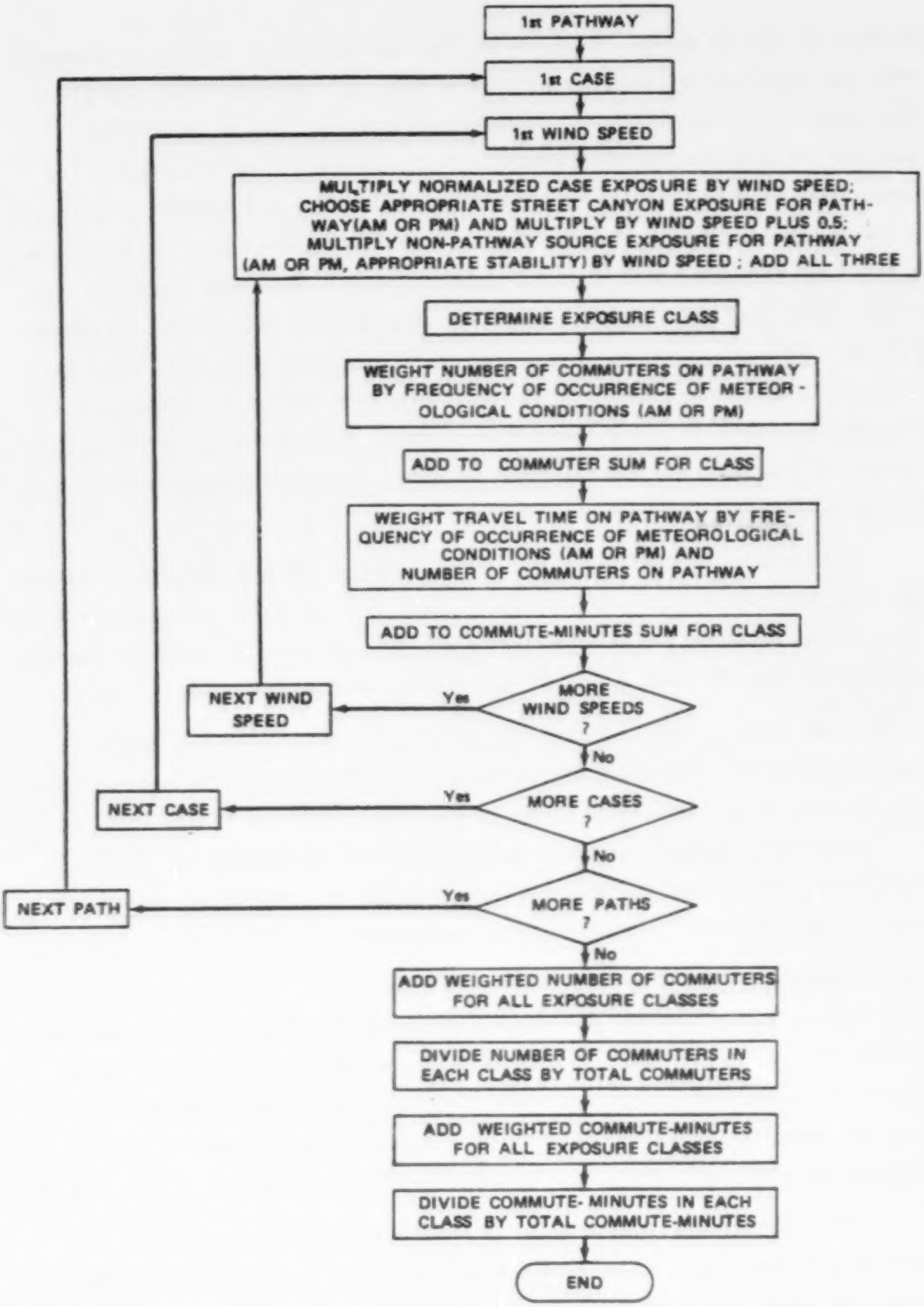

1st PATHWAY
1st CASE
1st WIND SPEED
MULTIPLY NORMALIZED CASE EXPOSURE BY WIND SPEED; CHOOSE APPROPRIATE STREET CANYON EXPOSURE FOR PATHWAY(AM OR PM) AND MULTIPLY BY WIND SPEED PLUS 0.5; MULTIPLY NON-PATHWAY SOURCE EXPOSURE FOR PATHWAY (AM OR PM, APPROPRIATE STABILITY) BY WIND SPEED ; ADD ALL THREE
DETERMINE EXPOSURE CLASS
WEIGHT NUMBER OF COMMUTERS ON PATHWAY BY FREQUENCY OF OCCURRENCE OF METEOROLOGICAL CONDITIONS (AM OR PM)
ADD TO COMMUTER SUM FOR CLASS
WEIGHT TRAVEL TIME ON PATHWAY BY FREQUENCY OF OCCURRENCE OF METEOROLOGICAL CONDITIONS (AM OR PM) AND NUMBER OF COMMUTERS ON PATHWAY
ADD TO COMMUTE-MINUTES SUM FOR CLASS
MORE WIND SPEEDS ?
Yes
NEXT WIND SPEED
No
MORE CASES ?
Yes
NEXT CASE
No
MORE PATHS ?
Yes
NEXT PATH
No
ADD WEIGHTED NUMBER OF COMMUTERS FOR ALL EXPOSURE CLASSES
DIVIDE NUMBER OF COMMUTERS IN EACH CLASS BY TOTAL COMMUTERS
ADD WEIGHTED COMMUTE-MINUTES FOR ALL EXPOSURE CLASSES
DIVIDE COMMUTE- MINUTES IN EACH CLASS BY TOTAL COMMUTE-MINUTES
END

FIGURE 16. FLOWCHART SHOWING HOW ANNUAL HISTOGRAM DATA ARE GENERATED

commuters on the pathway. It then will weight both the number of commuters (commuting vehicles multiplied by the number of commuters per vehicle) on the pathway and the pathway commuter-minutes by the frequency of occurrence of the case's wind speed, wind direction, and stability for the emission time period (morning or evening). The two weighted numbers will be stored for the exposure class. The model will then cycle to the next wind speed and repeat the procedure, then to the next case (of the 160) for each wind speed, and so forth. For each pathway, the weighted number of commuters will be summed for each exposure class, as will be the weighted commuter-minutes. Finally, the percentage of commuters in each exposure class will be found by dividing the number in the class by the total commuters; percentages of commuter-minutes (probabilities) will be found similarly.

If the user desires one or more subsets of the preceding information, he may request it with model input. For example, if pathway X is of particular interest, the user can input a flag and the pathway number to produce either or both types of histogram data for pathway X only.

One other type of output will be available when the model is in the annual mode. If information about the variation with meteorology of exposure on a particular pathway is desired, the user will input a flag, the pathway number, and the meteorological conditions of interest, and the model will list the morning and evening exposures on the pathway for each combination of meteorological parameters.

3. Graphical Display of Statistics

Histograms provide a convenient means of depicting the statistics generated by the model, with the added feature that a subroutine can be easily added to the model to generate the plots on a line printer. Classes of exposure or dose will be plotted on the abscissa, while the percentage of commuters or commuter minutes will be plotted on the ordinate.

For the annual statistics, it is more convenient to plot the results in a format analogous to a wind rose, with a separate plot for each set of meteorological and other conditions. In this case, each spoke will be associated with a pathway by numbering. Directionality will not be implied. Spoke width, expanding radially, will be associated with exposure or dose class, and the length of a spoke at each width will give the percentage data. The characteristics of each pathway relative to other pathways for each set of conditions will be easily discernible from such plots.

Alternatively, plots may be made for each pathway with the spokes referring to different conditions. This will serve to pinpoint the less desirable conditions for each roadway.

4. Summary of Model Output

The various types of model output generated by the numerical commuter exposure model have been discussed in the preceding paragraphs. Table 8 contains a summary of model output for both the short-term and annual modes of operation.

A final note should be made regarding the interpretation of the statistics generated by the model. As discussed previously, the commuter pathways do not account for all of the commuting in the modeled region. The number and complexity of the commuting routes in most metropolitan areas render a computer simulation of the complete commuting picture nearly impossible. Given this initial limitation for all cities, the model nevertheless can consider a larger percentage of the total commuters in some cities than it can treat in other cities. The percentage of commuters treated by the model is dependent not only on the size of the modeling area and the numbers of actual commuting routes in the area, but also on the user's choice of routes and the number of routes defined. For most cities sufficient data are available from which the user can determine the total number of commuters in the area and thus the percentage of the total commuters traveling on the commute pathways the user has defined. In interpreting model-produced statistics, the user should remember that the statistics only apply to this percentage of the commuters. In addition, the user knows that commuters traveling on the pathways by definition have relatively long commutes, and hence are at risk of high exposure. By the same token, the commuters "skipped" by the suggested method for pathway definition are those commuters with short home-to-work trips or having

Table 8

NUMERICAL COMMUTER EXPOSURE MODEL OUTPUT

Output in Short-Term Mode of Model Operation

List of exposures on each pathway

Average and standard deviation of exposures on pathways in modeled region

Percentage of commuters in each of several exposure classes

Probability of experiencing exposure levels in each of several exposure classes

Output in Annual Mode of Model Operation

Percentage of commuters in each of several exposure classes (for all pathways)

Probability of experiencing exposure levels in each of several exposure classes (for all pathways)

*Percentage of commuters in each of several exposure classes (on any single pathway)

*Probability of experiencing exposure levels in each of several exposure classes (on any single pathway)

*Pathway concentration associated with different meteorological conditions

*Pollution roses (see text on graphical display of statistics)

*Optional output

non-centralized places of employment. Thus, the commuter exposure statistics developed by the model will be biased toward high exposure levels.

G. Summary of Numerical Methodology

The details of the numerical commuter exposure modeling methodology have been discussed in the previous sections. The following is a summary of the overall model structure.

The first step in the application of the model involves the definition of the area to be modeled. To describe the pollutant concentrations to which the commuter is exposed, one must quantify the sources of the pollutant and prepare them for input to the model. The model user must prepare two types of data that will define the pollutant sources (i.e., traffic). First, the network of pathways on which the majority of commuters will travel must be identified. Computational problems would result if a large number of pathways were defined, so the user must choose only those pathways that are heavily traveled, and on which commuters are likely to experience high levels of exposure. Each pathway will be broken into a number of segments, according to roadway type. If a pathway has an abrupt change of direction, additional segments should be defined so that each segment approximates a straight line. Various parameters describing each of the segments will be input to the model.

The other type of traffic data that will be required by the model concerns motor vehicle pollutant sources that do not travel on the pathways. Since the majority of pathway exposure will result from traffic on the pathways themselves, information concerning non-pathway pollutant sources need not be extremely detailed. Therefore, the user will overlay the study area with a grid system and will assign the total vehicle miles traveled on the non-pathway street network to the grid system. This information, along with the locale (land use) type of each grid square, will be input to the model. The user will have the option of inputting gridded emission rates, rather than traffic data, directly if such data are available.

The numerical model will be capable of producing two kinds of output, one giving annual statistics, and the other describing short-term, worst-case exposure for a single commute. When the model is to be used in the annual mode, the user will input meteorological data in the form of two joint frequency distributions, describing the average morning and average evening hour of the commute. The frequency distributions will describe the joint frequency of occurrence of wind speed, wind direction, and stability over an average year. For the short-term mode of model operation, the user will input the meteorological conditions of each hour of the commute being analyzed.

Given the data described above as model input, the model will compute commuter exposures in the manner illustrated in Figure 17. First, calculations will be made of exposures resulting from pathway sources. For freeway, expressway, and non-CBD arterial segments of pathways, average route speed will be used to compute FTP emission rates on the segment; travel time will also be computed. On CBD arterials, the effects of signalization and congestion will be accounted for, and modal emissions, as well as travel time, will be computed for each segment. In the annual mode of model operation, emission rates for both the morning and evening commutes on each pathway will be calculated; in the short-term mode, a single emission rate on each pathway will be found (but traffic volume will be allowed to vary with time and to affect emissions).

Normalized exposures on each segment will be computed from emission rates, through the use of different dispersion on methodologies according to whether the segment is a street canyon; limited access; or non-limited access, non-street canyon. Table 9 lists the dispersion algorithms used for each roadway type. In the annual mode, 160 wind speed normalized exposures will be produced for each non-street-canyon segment, corresponding to all combinations of 16 wind directions, five stabilities, and two emission rates (morning and evening). On street-canyon segments, exposure is not a function of wind direction or stability. Therefore, only two normalized exposures will be produced for each segment, corresponding to morning and evening emissions. In the short-term mode, one exposure for each segment will be computed, using the meteorology appropriate to the hour during which the segment is traveled.

Next, calculations for non-pathway sources will be made. If gridded emissions are input directly, the model will simply convert daily emissions to average hourly emissions for each grid square (morning and evening

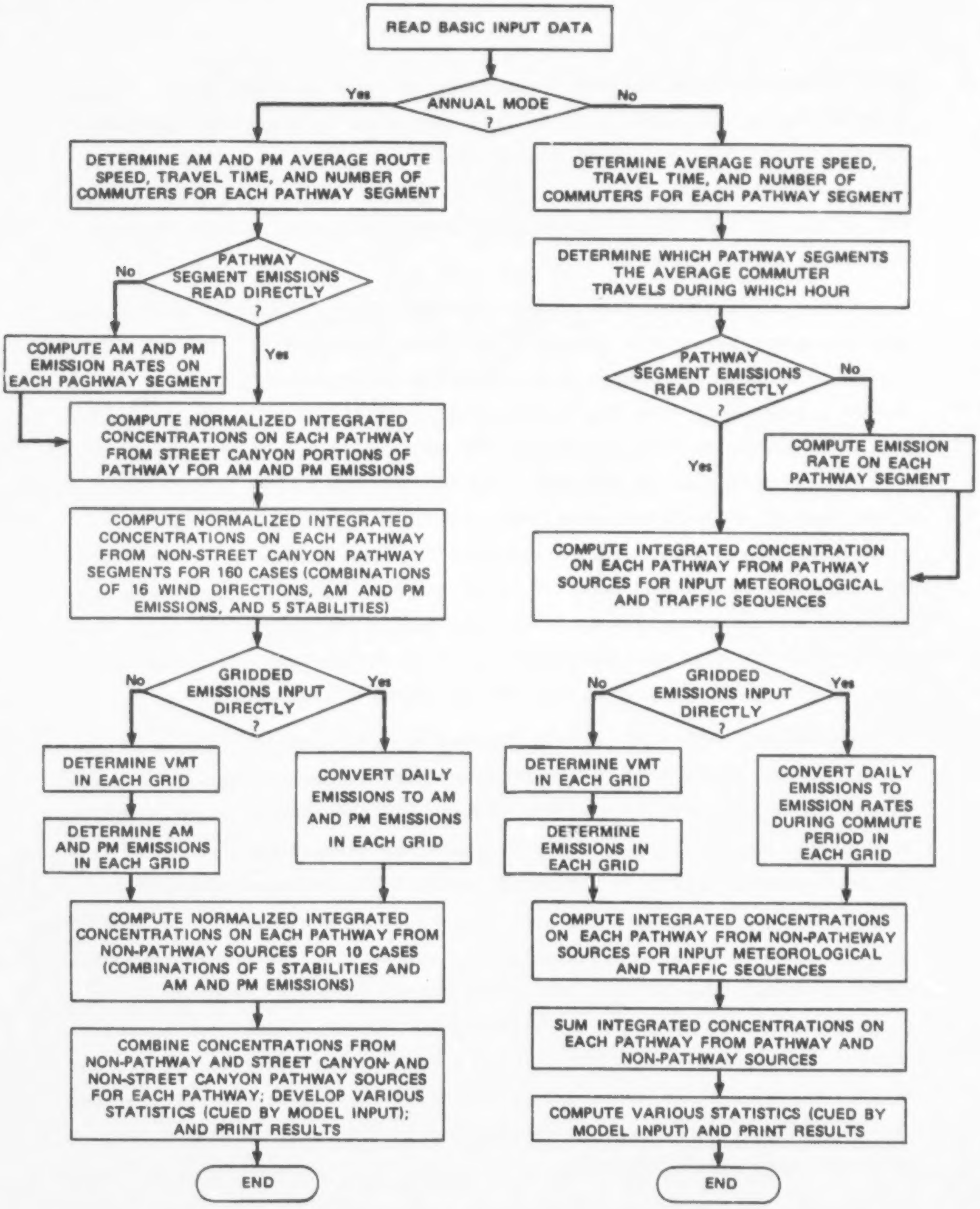

READ BASIC INPUT DATA
ANNUAL MODE ?
Yes
No
DETERMINE AM AND PM AVERAGE ROUTE SPEED, TRAVEL TIME, AND NUMBER OF COMMUTERS FOR EACH PATHWAY SEGMENT
PATHWAY SEGMENT EMISSIONS READ DIRECTLY ?
No
Yes
COMPUTE AM AND PM EMISSION RATES ON EACH PAGHWAY SEGMENT
COMPUTE NORMALIZED INTEGRATED CONCENTRATIONS ON EACH PATHWAY FROM STREET CANYON PORTIONS OF PATHWAY FOR AM AND PM EMISSIONS
COMPUTE NORMALIZED INTEGRATED CONCENTRATIONS ON EACH PATHWAY FROM NON-STREET CANYON PATHWAY SEGMENTS FOR 160 CASES (COMBINATIONS OF 16 WIND DIRECTIONS, AM AND PM EMISSIONS, AND 5 STABILITIES)
GRIDDED EMISSIONS INPUT DIRECTLY ?
No
Yes
DETERMINE VMT IN EACH GRID
DETERMINE AM AND PM EMISSIONS IN EACH GRID
CONVERT DAILY EMISSIONS TO AM AND PM EMISSIONS IN EACH GRID
COMPUTE NORMALIZED INTEGRATED CONCENTRATIONS ON EACH PATHWAY FROM NON-PATHWAY SOURCES FOR 10 CASES (COMBINATIONS OF 5 STABILITIES AND AM AND PM EMISSIONS)
COMBINE CONCENTRATIONS FROM NON-PATHWAY AND STREET CANYON AND NON-STREET CANYON PATHWAY SOURCES FOR EACH PATHWAY; DEVELOP VARIOUS STATISTICS (CUED BY MODEL INPUT); AND PRINT RESULTS
END
DETERMINE AVERAGE ROUTE SPEED, TRAVEL TIME, AND NUMBER OF COMMUTERS FOR EACH PATHWAY SEGMENT
DETERMINE WHICH PATHWAY SEGMENTS THE AVERAGE COMMUTER TRAVELS DURING WHICH HOUR
PATHWAY SEGMENT EMISSIONS READ DIRECTLY ?
No
Yes
COMPUTE EMISSION RATE ON EACH PATHWAY SEGMENT
COMPUTE INTEGRATED CONCENTRATION ON EACH PATHWAY FROM PATHWAY SOURCES FOR INPUT METEOROLOGICAL AND TRAFFIC SEQUENCES
GRIDDED EMISSIONS INPUT DIRECTLY ?
No
Yes
DETERMINE VMT IN EACH GRID
DETERMINE EMISSIONS IN EACH GRID
CONVERT DAILY EMISSIONS TO EMISSION RATES DURING COMMUTE PERIOD IN EACH GRID
COMPUTE INTEGRATED CONCENTRATIONS ON EACH PATHWAY FROM NON-PATHEWAY SOURCES FOR INPUT METEOROLOGICAL AND TRAFFIC SEQUENCES
SUM INTEGRATED CONCENTRATIONS ON EACH PATHWAY FROM PATHWAY AND NON-PATHWAY SOURCES
COMPUTE VARIOUS STATISTICS (CUED BY MODEL INPUT) AND PRINT RESULTS
END

FIGURE 17. SIMPLIFIED FLOW CHART FOR NUMERICAL COMMUTER EXPOSURE MODEL

Table 9

DISPERSION ALGORITHMS USED IN NUMERICAL MODEL

Roadway Type	Dispersion Algorithm Source	Algorithm Type	Required Input Data
limited-access pathway	ROADMAP	Gaussian, 2-component	emission rate, roadway width wind speed, wind direction, stability
non-limited-access pathway	CALINE2*	Gaussian, 2-component	emission rate, roadway width, wind speed, wind direction, stability
street canyon pathway	APRAC	empirical	emission rate, wind speed
non-pathway	Hanna-Gifford	simplified Gaussian	emission rate, wind speed, stability

*Subject to change

values for the annual mode, single values for the short-term mode). If traffic data are input, the model will compute the values described above from the traffic and locale data. Once gridded data on emissions are available, the model, in the annual mode, will compute morning and evening wind speed normalized integrated concentrations, for each of five stabilities, on each pathway. In the short-term mode, an integrated concentration for each pathway will be produced.

The model now will have computed the exposure values, for each segment, needed to develop annual or short-term commuter exposure statistics. In the annual mode, the appropriate non-street canyon, street canyon, and non-pathway exposures for each segment will be multiplied by wind speed and combined. Segment exposures will be summed for each pathway. As appropriate, each of the pathway exposures will be weighted by either the morning or evening frequency of occurrence of the meteorological conditions used to compute the exposure value. Those exposures will then be used in the development of various annual statistics describing commuter exposure In the short-term mode, the model will simply combine pathway and non-pathway exposures for each segment and sum over the pathway. The resulting pathway exposure will be used to develop short-term, worst-case commuter exposure statistics.

III MANUAL COMMUTER EXPOSURE MODEL

A. General

The manual commuter exposure modeling methodology is similar to the numerical methodology in terms of the individual methodologies of the three model components, traffic, emissions, and dispersion. The major difference between the manual and numerical models is in the degree of complexity of the commuting with which each model can deal. Because the numerical model is executed on a computer, a large number of computations may be made rapidly. On the other hand, manual model computations are made at best on a desk calculator; a large number of computations would be both time-consuming and prone to error. Therefore, the commuting situations that can be analyzed with the manual model are limited. While the numerical model can produce annual or short-term commuter exposure statistics for a number of pathways, the manual model is, practically, limited to the analysis of a short-term, worst-case commute on one pathway or a small number of them. Since the generation of enough pathway exposures to produce exposure statistics is time-prohibitive with the manual model, its value may lie in use as a screening tool for planning. If application of the manual model indicates a potential problem, the numerical model can be applied to analyze the situation in greater detail.

The manual model will be comprised of a series of worksheets, instructions for completing each worksheet, and a number of charts, tables, and nomographs similar to those presented in the following sections. To apply the manual model the user will follow the procedure outlined below. The user will read the instructions concerning definition of the modeling area and gather the necessary information to define pathway and non-pathway sources. The next step will be to fill in the first worksheets with the necessary traffic information. Each worksheet will have a series of instructions that detail the nature of the information required for the worksheet and a source of such information. In some cases the source will be one of the charts, tables, or nomographs included in the user's guide to the model. In other cases, the information must be obtained from a local or state agency.

Once the traffic worksheets have been completed, some of the parameters computed will be transferred to the emissions worksheet, and the emissions worksheets will be filled out according to their instructions. Finally, the pathway segment emission rates (from the emissions worksheets), along with the number of computers on the pathway and the segment travel times (from the traffic worksheets), will be entered on the dispersion worksheets. The user also will enter the meteorological parameters and, following the dispersion worksheet instructions, use the appropriate tables and figures to complete the worksheets. The output of the dispersion worksheets will be the pathway exposure.

The following sections describe the manual methodology for defining the modeling approach, and treating traffic, emissions, and dispersion. The approach assumes that computations are made for a single commute, with meteorology and traffic held constant over the commute.

B. Definition of Modeling Approach

As discussed for the numerical model, proper definition of the modeling area is vital to having a tractable problem. In general, the definition of the modeling area for the manual model will be the same as for the numerical model.

1. Commuter Pathways

The commuter pathways may be defined in the same manner as for the numerical model. It may be desirable to choose considerably fewer pathways, ranked by traffic flow conditions, because the manual computations will be by necessity somewhat cumbersome. The number of pathways to be analyzed will depend on the resources available to do the manual modeling. Again, the local transportation agency should be called for assistance in choosing pathways and determining their characteristics.

2. Non-Pathway Sources

As for the numerical commuter model, non-pathway sources consist of the vehicles traveling on all of the roadways in the study area other than commuter pathways. In the manual model, the emissions and dispersion from non-pathway sources will be treated in the same manner as they would be for the numerical model. The user will overlay the commuter pathway (or pathways) being analyzed with a 2-km-by-2-km grid system. Primary traffic network VMT (excluding the pathway) will be apportioned to the grid squares as described for the numerical model. Secondary network VMT will be computed by the user. It will be equal to the primary network VMT of the grid square multiplied by the ratio of secondary to primary traffic associated with the locale type of the square. The user will combine primary and secondary VMT for each grid.

In the numerical model, it is necessary to consider all grid squares through which commuter pathways pass, even though the dispersion treatment does not use all grid squares. Since the model is a black box to the user, the grid squares that are used cannot easily be determined. It is simply more efficient to require input for all grid squares. However, in the manual model, all computations must be made by hand, so those grid squares that will be used will be familiar to the user. Therefore, the VMT for all grid squares through which pass commuter pathways need not be computed. Those grids for which information will be required can be identified once the user understands how dispersion computations for non-pathway sources will be made.

C. Traffic Modeling

Traffic modeling in the manual model will use the same formalism as in the numerical model. However, the manual use of graphs and nomographs as well as hand calculations will be substituted for calculations performed by the computer.

1. Uninterrupted Flow

Derivation of volume, capacity, and average speed may be accomplished in the same manner as that described for the numerical model, for pathway segments that have uncongested flow. The only difference is that the user will hand-calculate capacity based on the type of roadway and adjustment factors being considered, rather than have the option of letting the model perform the computation.

Congested segments may be modeled by nomographs, as shown in Figures 18 and 19. The nomographs are based on equations presented in the section of this report that discusses the numerical model. In Figure 18, the user enters the nomograph with the length of time that demand (volume) exceeds capacity, selects the appropriate value of demand volume minus capacity, connects that point with the volume-to-capacity ratio for the time that capacity exceeds demand, and finds the total number of vehicles in the backup, $\hat{N}$, from the bottom left-hand scale. The number of vehicles backed up while demand exceeds capacity, N, is read from the abscissa.

Figure 19 may be used to find the average delay per vehicle (time to traverse the portion of the roadway on which the backup occurs). The values of N and $\hat{N}$ must be known. The user enters the top left-hand scale at N, connects that point horizontally with the solid line, then moves vertically to the value of $\hat{N}$ from among the family of curves on the bottom graph. The average delay per vehicle is then read from the bottom left-hand scale. The dashed lines on Figures 18 and 19 show the procedure for the example presented for the numerical model.

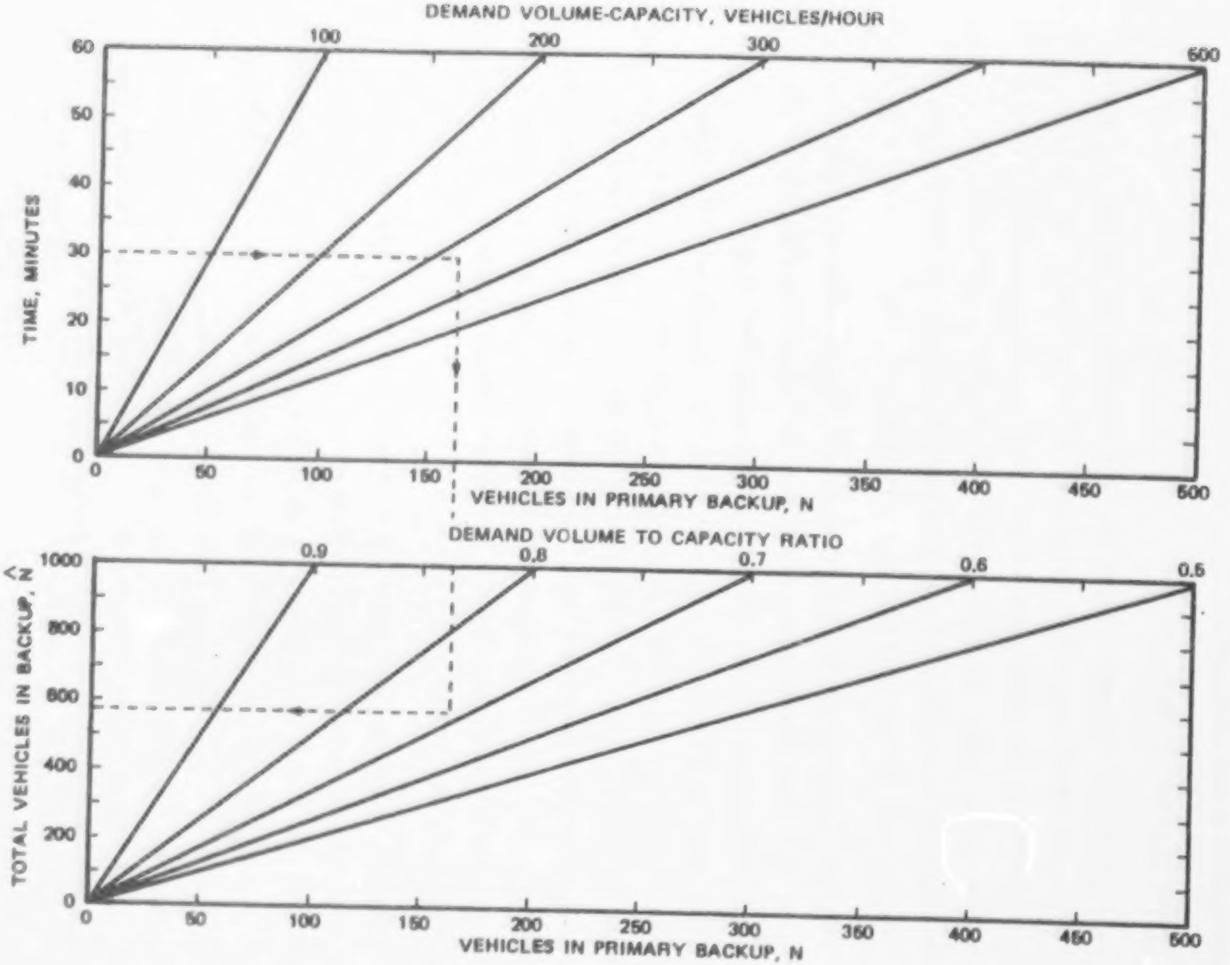


FIGURE 18. NOMOGRAPH FOR FINDING THE EXTENT (VEHICLES) OF THE PRIMARY BACKUP, N, AND THE TOTAL BACKUP, $\hat{N}$, FROM DEMAND VOLUME, CAPACITY, AND TIME FOR CONGESTED, UNINTERRUPTED FLOW

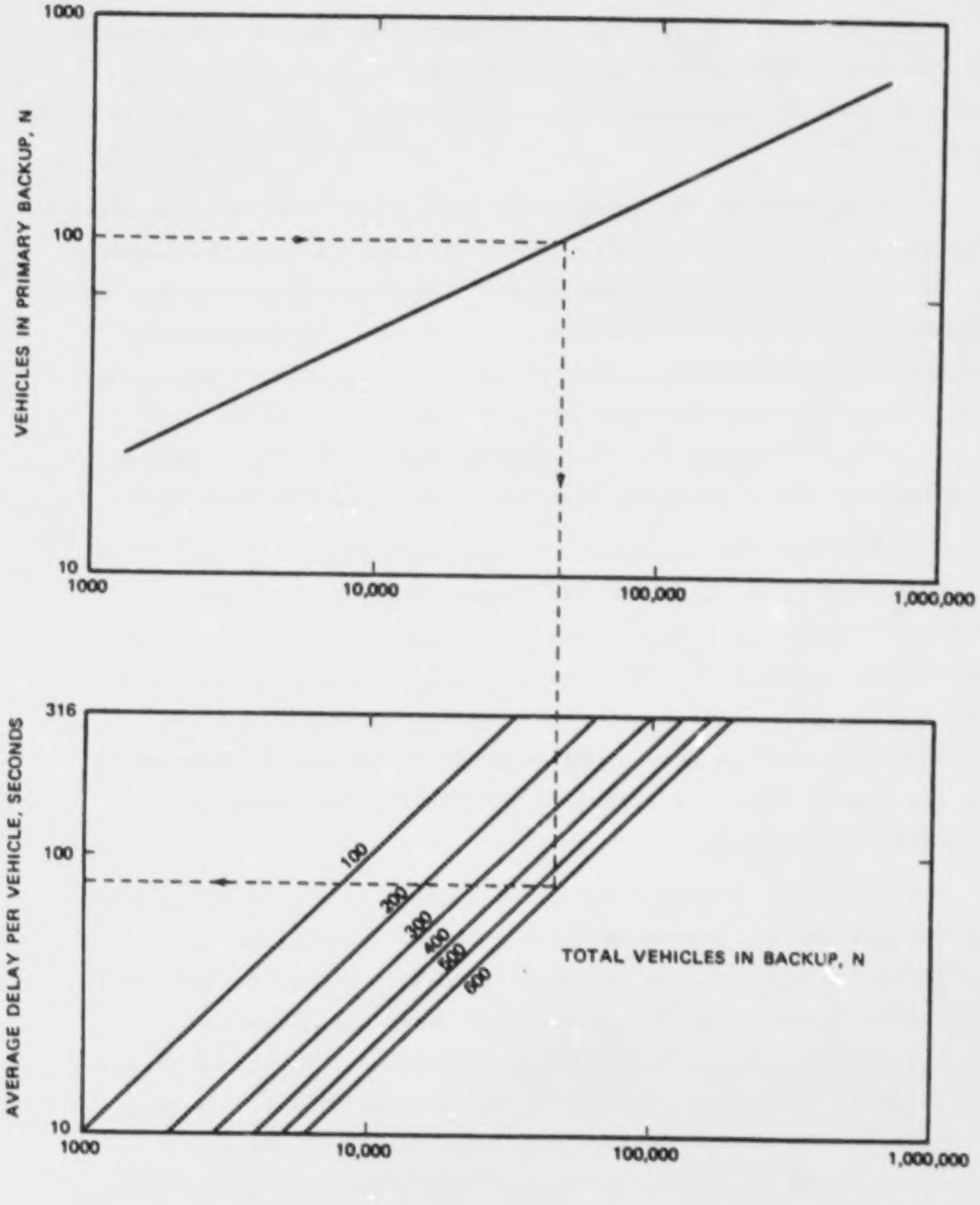


FIGURE 19. NOMOGRAPH FOR FINDING AVERAGE DELAY PER VEHICLE. SPEED = 20 MPH. HEADWAY = 1.8 SECONDS.

2. Interrupted Flow

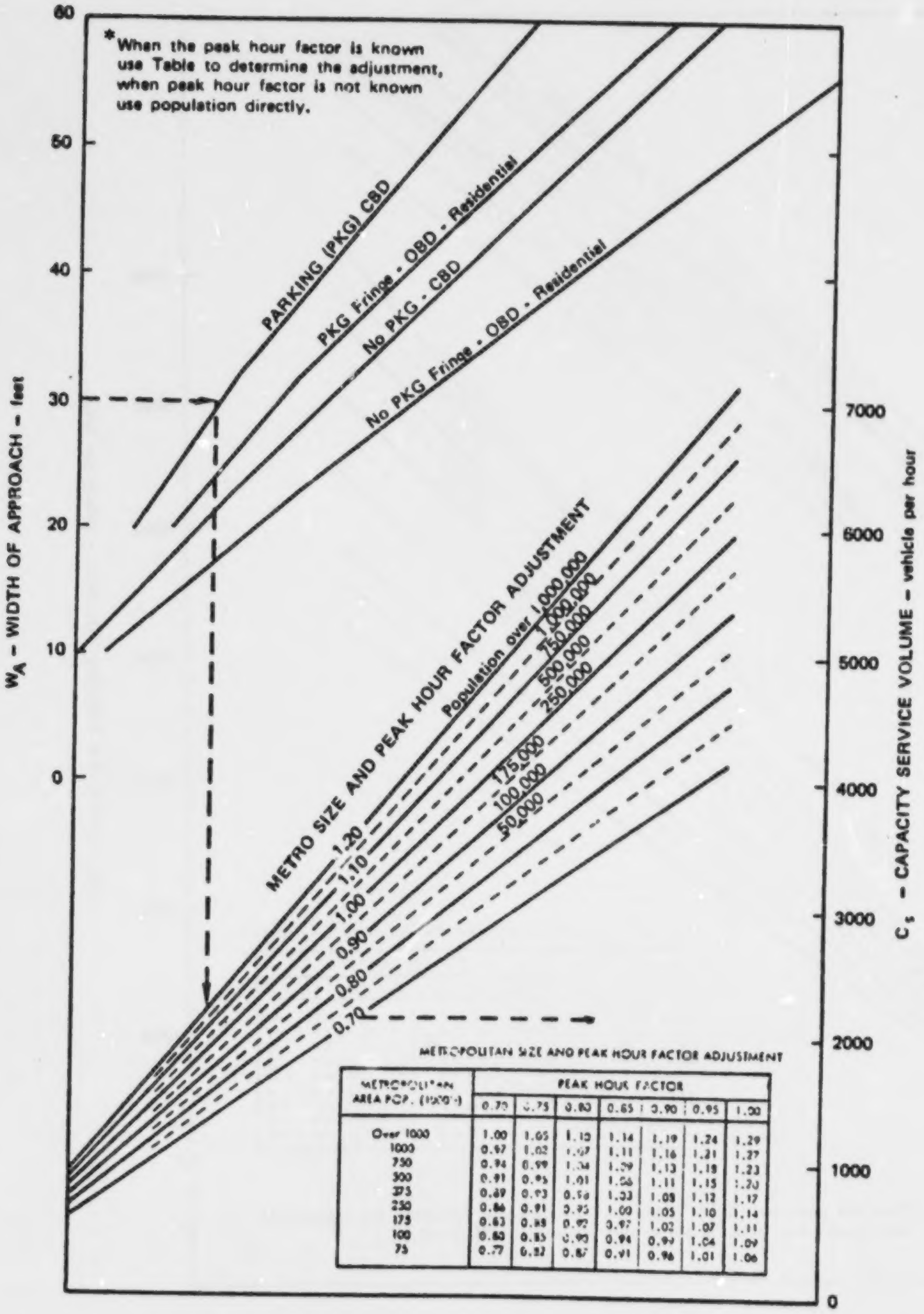
Average route speeds for interrupted flow outside the central business district (CBD) may be obtained through the use of Figure 7; reference is made to the discussion in the numerical model section of this report.

For calculating the interrupted flow within the CBD, the starting point is again to find the capacity service volume, Cs, and the demand volume, V, on the intersection approaches. Capacity service volume may be found using the nomograph presented for the numerical methodology, or alternatively, the simpler nomographs given in Figures 20 and 21 may be used. The green time-to-signal cycle ratio, G/Cs, must be hand-calculated using the numerical model methodology. Ideally, values of these parameters may be obtained from the local transportation agency.

Once known, the values may be used with Figures 22 and 23 to calculate the number of stops and the average delay per vehicle. Figure 22 is a graphical presentation of the signalized intersection queueing equations given for the numerical model. The user must know the capacity service volume of the intersection approach, C_s, the demand volume, V, and the green time-to-cycle length ratio. The dashed line on the figure shows the procedure for finding the number of vehicles stopping per hour.

Figure 23 is based on equations similar to the delay equation of the numerical model, except it results in the calculation of average delay for all vehicles on the intersection approach. The user must calculate the capacity of the approach under signalization, GCs/Cy. That is merely the capacity service volume per hour of green, Cs, multiplied by the fraction of the time that the signal is green, G/Cy. Denoting that as C, the user must also supply the degree of saturation, S, found by taking the ratio of the demand volume to the capacity, V/C.

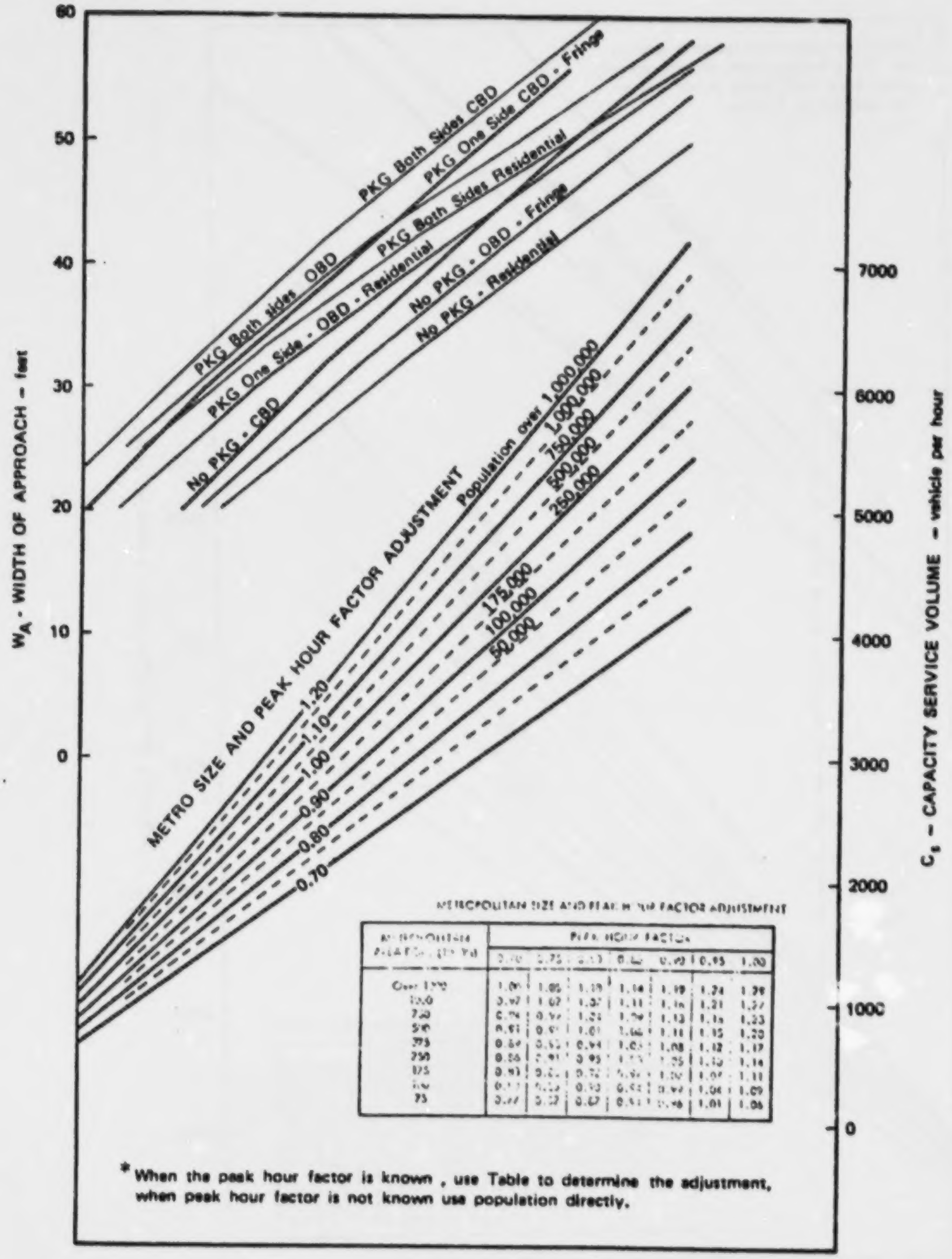
Figure 24 may be used to find the average delay per vehicle at toll booths. Again, it is based on the toll-booth-delay equation in the



METROPOLITAN SIZE AND PEAK HOUR FACTOR ADJUSTMENT

METROPOLITAN AREA POP. (1000's)	PEAK HOUR FACTOR						
	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Over 1000	1.00	1.05	1.10	1.14	1.19	1.24	1.29
1000	0.97	1.02	1.07	1.11	1.16	1.21	1.27
750	0.94	0.99	1.04	1.09	1.13	1.18	1.23
500	0.91	0.95	1.01	1.06	1.11	1.15	1.20
375	0.89	0.93	0.98	1.03	1.08	1.12	1.17
250	0.86	0.91	0.95	1.00	1.05	1.10	1.14
175	0.83	0.88	0.92	0.97	1.02	1.07	1.11
100	0.80	0.85	0.90	0.94	0.99	1.04	1.09
75	0.77	0.82	0.87	0.91	0.96	1.01	1.06

FIGURE 20. TWO WAY STREET CBD, FRINGE, OBD AND RESIDENTIAL CAPACITIES

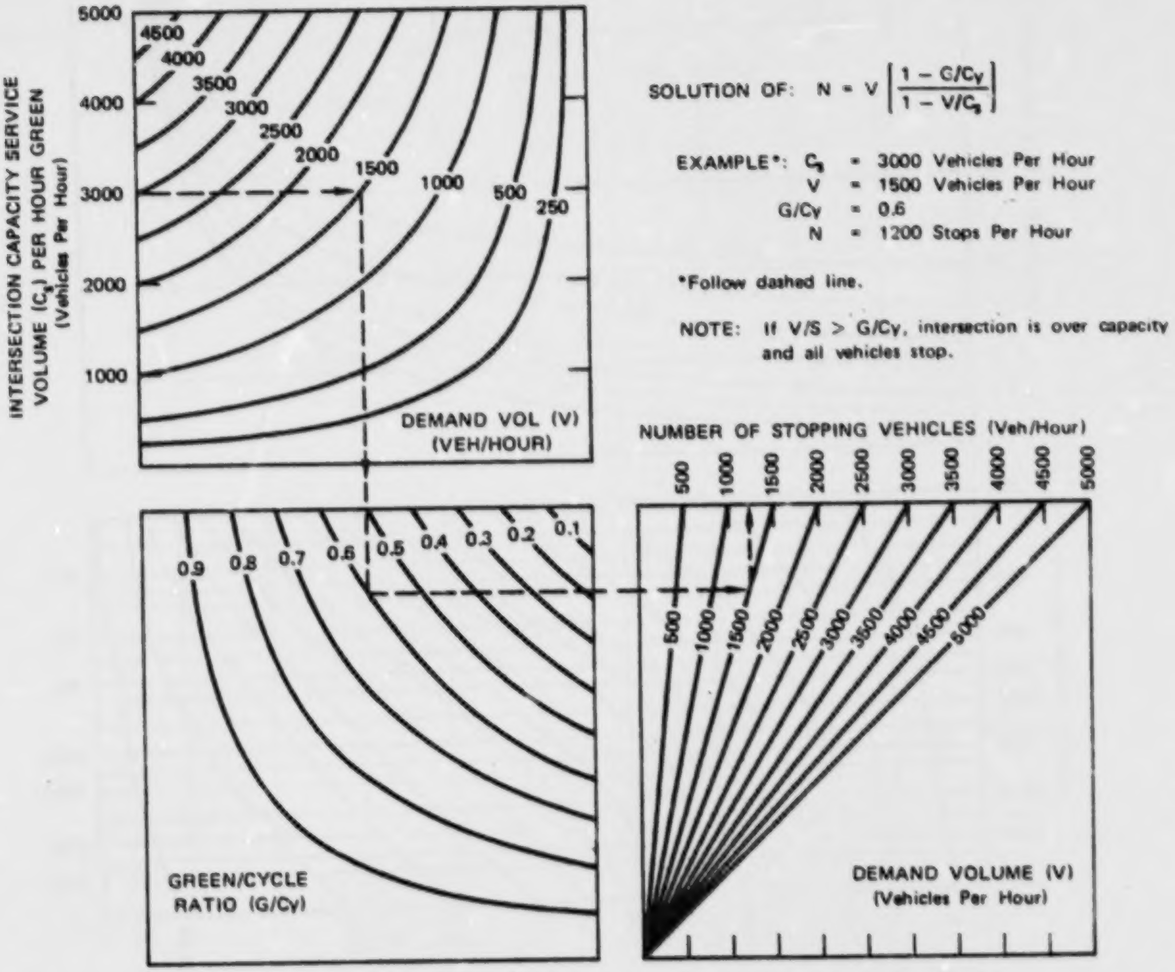


METROPOLITAN SIZE AND PEAK HOUR FACTOR ADJUSTMENT

[illegible]	PEAK HOUR FACTOR						
	0.70	0.75	0.80	0.85	0.90	0.95	1.00
Over 1000	1.00	1.05	1.10	1.14	1.19	1.24	1.29
1000	0.97	1.02	1.07	1.11	1.16	1.21	1.27
750	0.94	0.99	1.04	1.09	1.13	1.18	1.23
500	0.91	0.96	1.01	1.06	1.11	1.15	1.20
375	0.89	0.93	0.98	1.03	1.08	1.12	1.17
250	0.86	0.91	0.95	[illegible]	1.05	1.10	1.14
175	0.83	[illegible]	0.92	[illegible]	1.02	1.07	1.11
100	0.80	[illegible]	0.90	0.95	0.99	1.04	1.09
75	0.77	0.82	0.87	0.91	0.96	1.01	1.06

*When the peak hour factor is known, use Table to determine the adjustment, when peak hour factor is not known use population directly.

FIGURE 21. ONE WAY STREET CBD, FRINGE, OBD AND RESIDENTIAL CAPACITIES



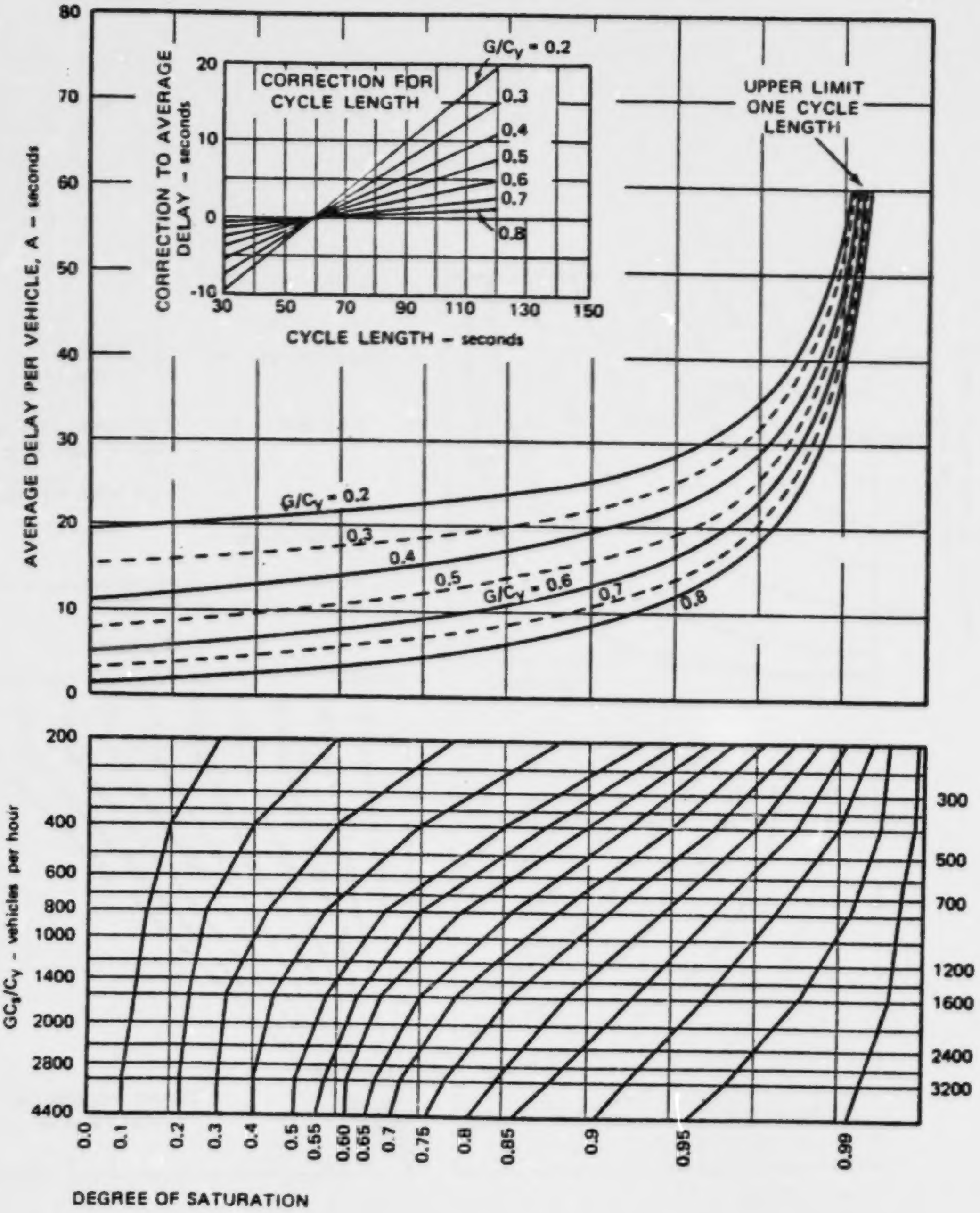
SOLUTION OF: $N = V \left[\frac{1 - G/C_y}{1 - V/C_s} \right]$

EXAMPLE*: C_s = 3000 Vehicles Per Hour
V = 1500 Vehicles Per Hour
G/Cy = 0.6
N = 1200 Stops Per Hour

*Follow dashed line.

NOTE: If V/S > G/Cy, intersection is over capacity and all vehicles stop.

FIGURE 22. GRAPHICAL ESTIMATION OF THE NUMBER OF VEHICLES PER HOUR STOPPING AT A SIGNALIZED INTERSECTION



where: S = V/C = degree of saturation
V = demand volume
C = GC_s/C_y = capacity under signalization
C_s = capacity service volume
G/C_y = green to cycle time ratio

FIGURE 23 INTERSECTION DELAY PER VEHICLE

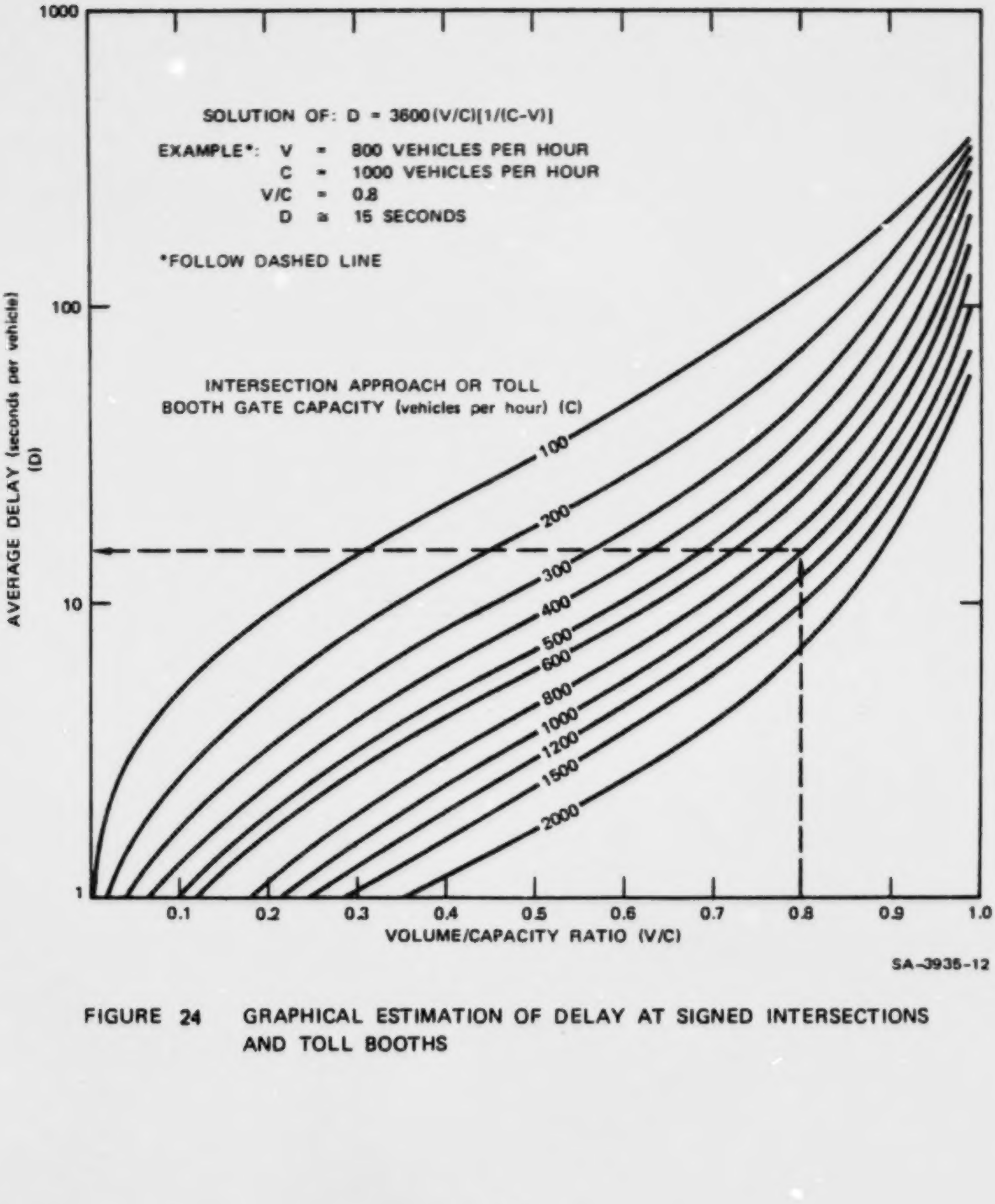


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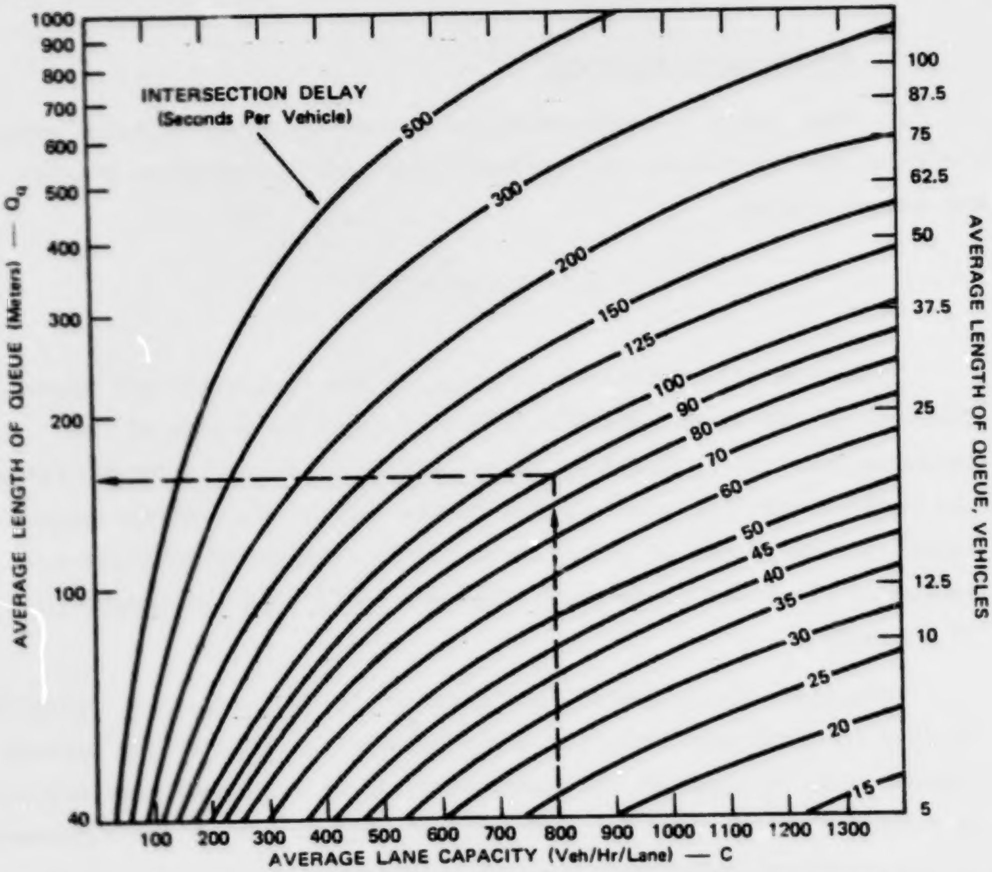
FIGURE 24 GRAPHICAL ESTIMATION OF DELAY AT SIGNED INTERSECTIONS AND TOLL BOOTHS

numerical model description. Queue lengths, in vehicles and in meters, can be found through the use of Figure 25 once the average delay is known.



SOLUTION OF: $X_q \cong \frac{DC}{450L}$

L = Number of Lanes

EXAMPLE*: LANE CAP. $\frac{C}{L}$ = 800 VEH/HR
DELAY = 90 SEC
QUEUE LENGTH = 160 METERS

*FOLLOW THE DASHED LINE

FIGURE 25 GRAPHICAL ESTIMATION OF QUEUE LENGTH AS A FUNCTION OF LANE CAPACITY AND INTERSECTION DELAY WITH A MINIMUM QUEUE LENGTH OF 40 METERS ASSUMED

D. Emissions Modeling

The treatment of emissions in the manual modeling methodology will be based on the same methods used for the numerical model. Again, the FTP and modal model treatments are applicable.

1. Emissions on Pathways

When there is uncongested flow, the following equation gives the relationship between the emission rate and the emission density and demand volume:

$$Q = \frac{EV}{(3600)(1609)}$$

Figure 26 illustrates how a graph of the equation might appear. The user of the manual model will have to develop values of the emission density, E, based on speed, altitude, state, calendar year, and vehicle mix. The user's guide to the manual model should include tables giving values of E for a nationwide average vehicle mix and ranges of the other parameters. The user could then use those values, if necessary.

When there is congested flow outside the CBD, values of emission density for both the free-flow and congested portions of the pathway segment must be found by the model user. An average emission rate will be computed by the user from the relationship presented and discussed in the numerical model section of this report.

Within the CBD, the modal emission treatment is applicable. Figure 27 can be used to find the acceleration and deceleration emissions, E_{AD}, idle emissions, E_I, and cruise emissions, E_C. The procedure for the emissions calculation is demonstrated by the dashed lines on the graph. They indicate that the emissions from deceleration and acceleration, with a cruise speed of 30 mi/hr, total 6.2 kg per 1,000 stops. Using the example of Figure 22, 1,200 stops/hr, and a cycle length of 90 sec, the excess emissions from deceleration and acceleration would be:

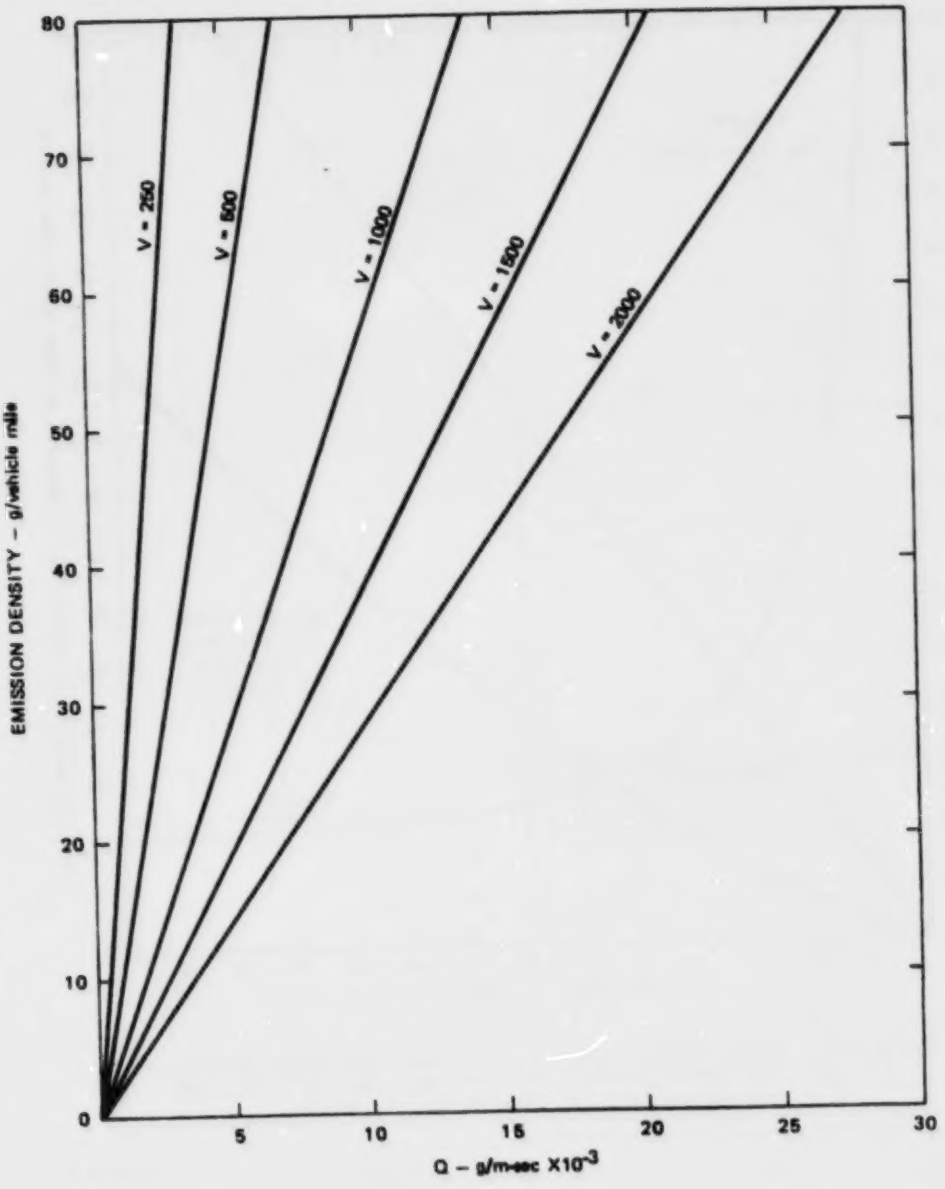
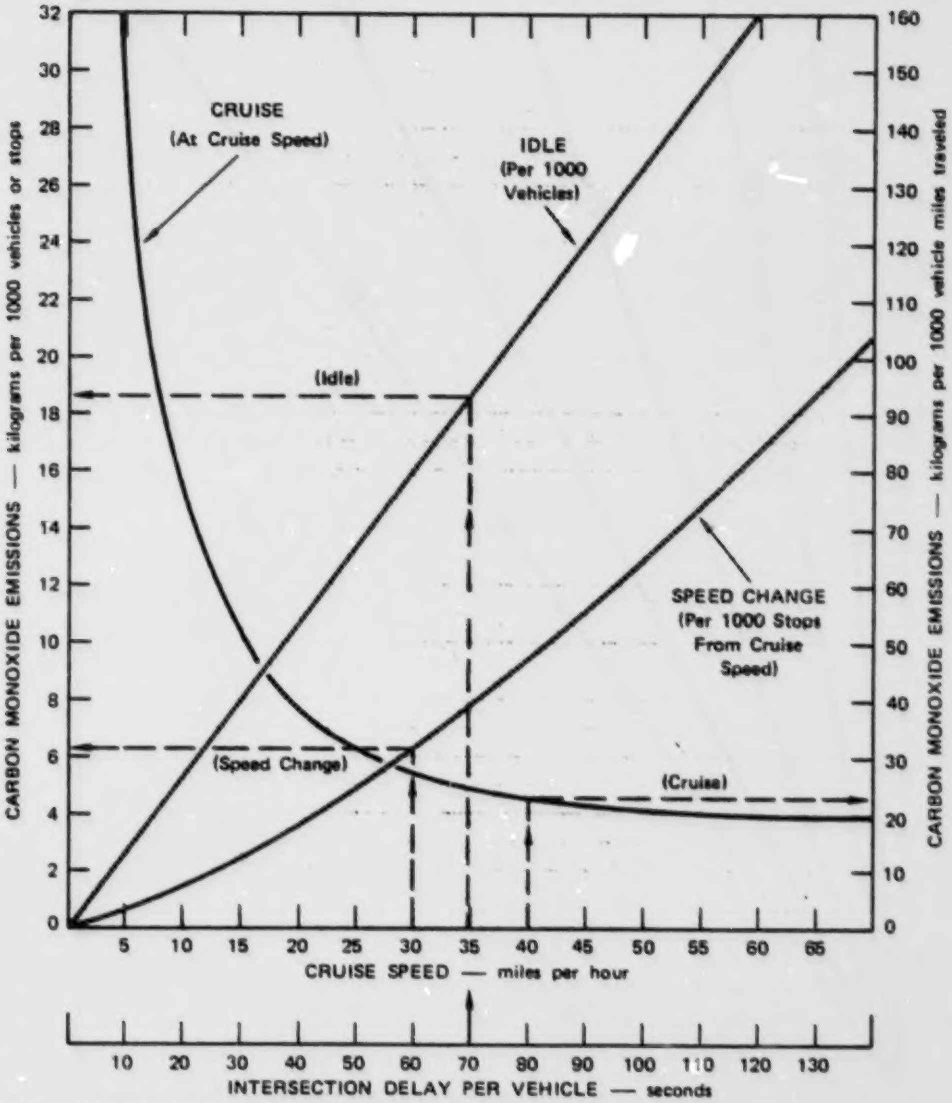


FIGURE 26 RELATIONSHIP BETWEEN EMISSION RATE AND EMISSION DENSITY AND DEMAND VOLUME



NOTE: Dashed lines illustrate calculation procedure.

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FIGURE 27 GRAPHICAL CALCULATION OF CARBON MONOXIDE EMISSIONS

$$E_{AD} = \left(\frac{6.2\ \text{kg}}{1000\ \text{stops}}\right) \left(\frac{1200\ \text{stops}}{3600\ \text{sec}}\right) \left(\frac{1000\ \text{g}}{1\ \text{kg}}\right) \div 8\ \text{m} \left(\frac{1200\ \text{stops}}{3600\ \text{sec}}\right)\left(\frac{90\ \text{sec}}{\text{cycle}}\right)$$

$$= 0.0086\ \text{g/m/sec.}$$

That can be expressed as

$$E_{AD} = E/8C_y,$$

where E = emissions per stop, g (= kg/1000 stops)

8 = a constant, representing the length of a stopped vehicle, m

C_y = cycle length, seconds.

Continuing to use the data from Figure 22, one finds the delay per vehicle from Figure 23 to be about 15 seconds. From Figure 27, idle emissions of 4 kg/1,000 vehicles/15 sec are indicated. Excess emissions from idling are thus:

$$E_I = \left(\frac{4\ \text{kg}}{(1000\ \text{veh})(15\ \text{sec})}\right) \left(\frac{1500\ \text{veh}}{1\ \text{hr}}\right) \left(\frac{15\ \text{sec}}{\text{veh}}\right) \left(\frac{1\ \text{hr}}{3600\ \text{sec}}\right)\left(\frac{1000\ \text{g}}{1\ \text{kg}}\right)$$

$$\div\ 8\ \text{m} \left(\frac{1200\ \text{stops}}{3600\ \text{sec}}\right) \left(\frac{90\ \text{sec}}{\text{cycle}}\right)$$

$$= 0.0069\ \text{g/m/sec}$$

or $$E_I = \frac{E}{8PC_y}\ \text{g/m/sec}$$

where

P = proportion of vehicles that stop.

Finally, cruise emissions at 30 mi/hr are 27 kg per 1,000 vehicle-miles traveled, according to Figure 27. That is equivalent to 27 g/mi;

E_C is thus:

$$E_C = \left(\frac{27\ \text{g}}{\text{vehicle mi}}\right) \left(\frac{1500\ \text{veh}}{3600\ \text{sec}}\right) \left(\frac{30\ \text{mi}}{3600\ \text{sec}}\right) \frac{\left(1\ \text{mi/hr}\right)}{\left(30\ \frac{\text{mi}}{\text{hr}}\right)\left(0.447\ \frac{\text{m}}{\text{sec}}\right)}$$

$$= 0.007\ \text{g/m/sec}$$

or $$E_C = \frac{EV}{(3600^2)(.44704)}$$

$$= 1.726 \times 10^{-7}\ EV$$

where V = demand volume, vehicles/hr.

As an alternative to the calculations of E_{AD}, E_I, and E_C, Figures 28 through 30 may be used. Those figures are used with Figure 27 and present graphical solutions to the equations presented in this section for calculating E_{AD}, E_I, and E_C in g/m/sec.

2. Non-Pathway Emissions

As in the numerical methodology, the manual model methodology will use FTP emission factors (emission density). The user will supply the emission factors corresponding to the cold-start percentages (for each of the five locale types) and the average temperature of the commute being analyzed. The user should assume the FTP average route speed of 19.6 mi/hr, and that all other correction factors are unity.

To compute an emission rate for the grid squares, first the daily VMT in the grid must be converted to VMT for the average hour of the commute. The conversion will be made by multiplying the daily VMT by the percentage of VMT during the average commute hour. (The percentage should be available for the area being analyzed from the local transportation agency.) The average hourly VMT will be multiplied by the appropriate emission factor, and the product will be divided by the

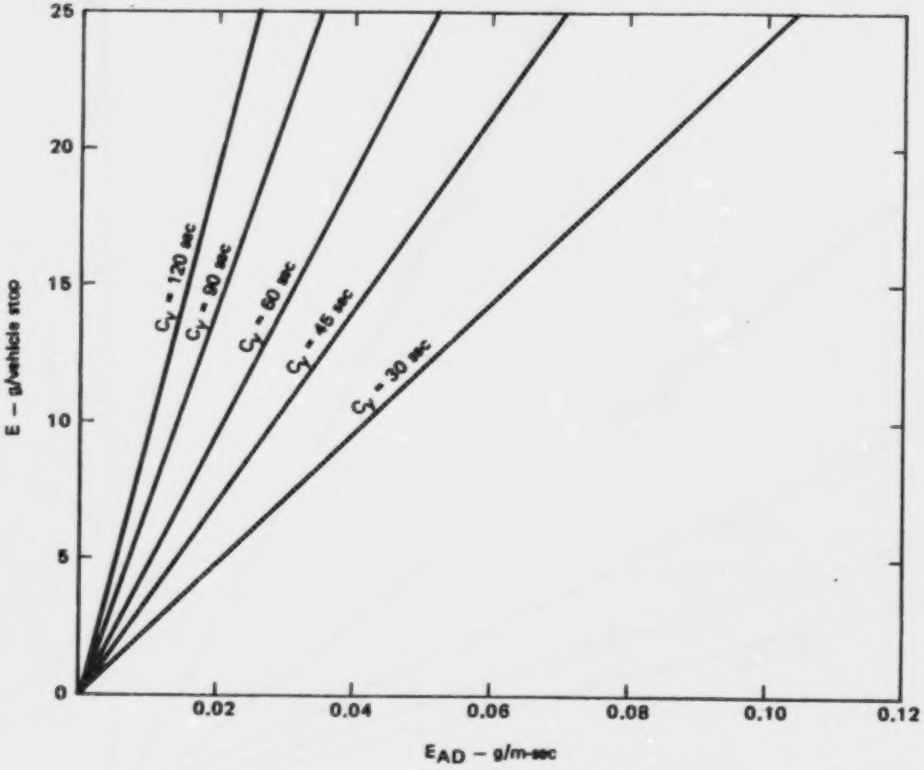

FIGURE 28 GRAPHICAL CALCULATION OF ACCELERATION/DECELERATION EMISSION RATE, G/M-SEC, GIVEN ACCELERATION/DECELERATION EMISSIONS FROM FIGURE 27 AND THE CYCLE LENGTH, C_y.

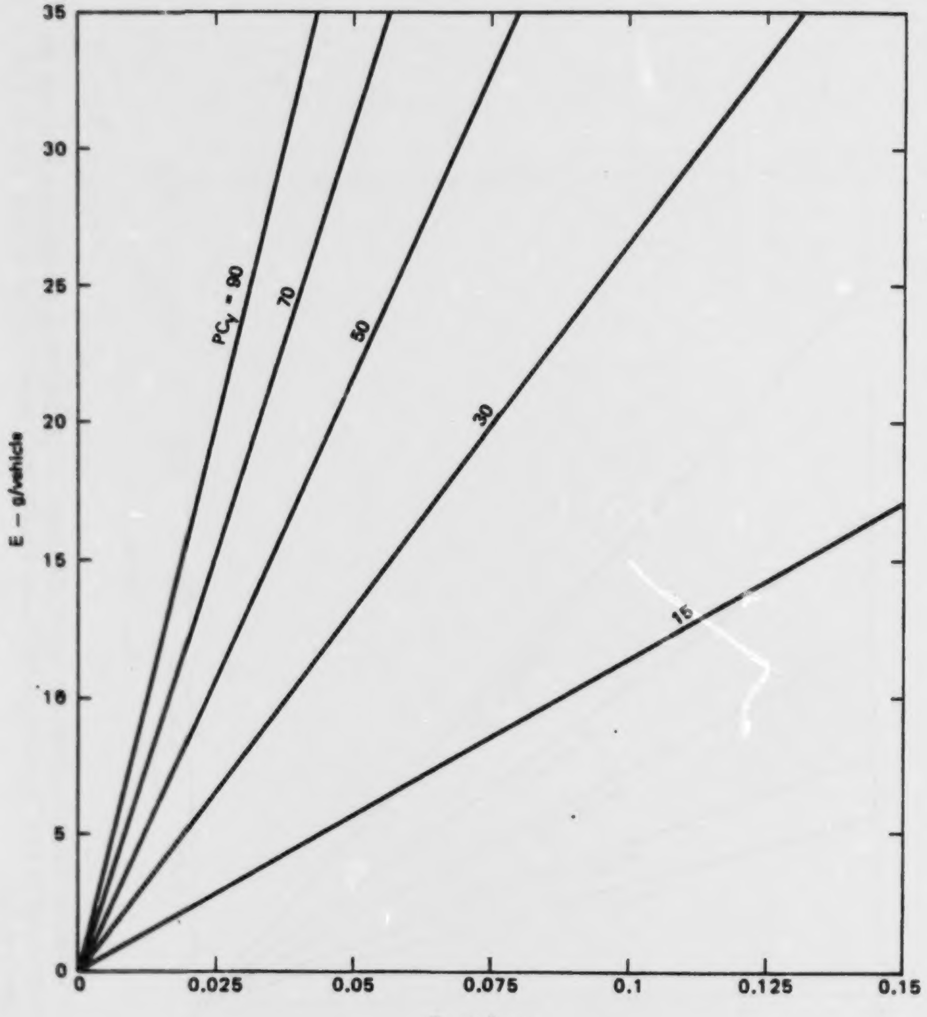

FIGURE 29. GRAPHICAL CALCULATION OF IDLE EMISSION RATE, G/VEH-SEC, GIVEN IDLE EMISSIONS FROM FIGURE 27 AND PC$_\gamma$.

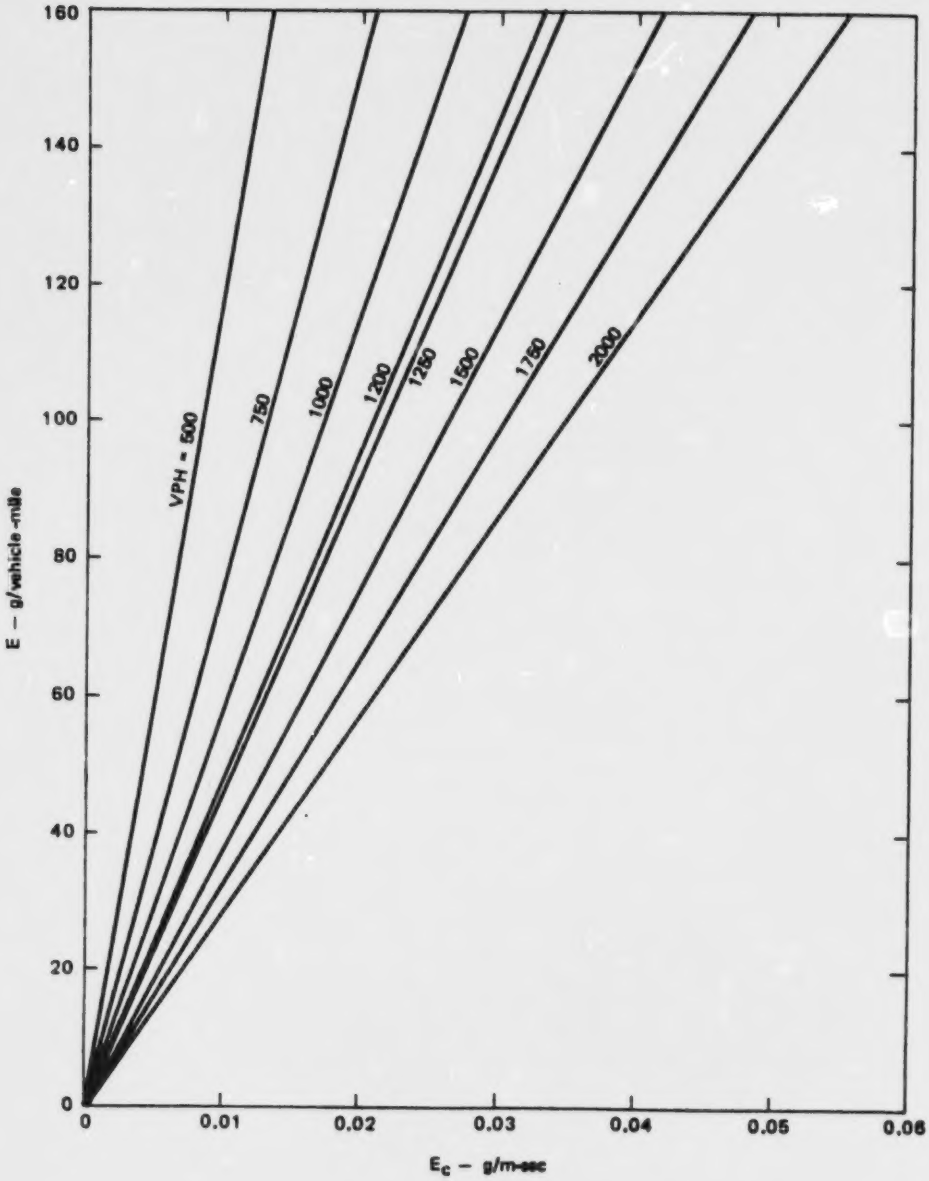

FIGURE 30. GRAPHICAL CALCULATION OF CRUISE EMISSION RATE, G/M-SEC, GIVEN THE G/VEH-MILE FROM FIGURE 27 AND THE DEMAND VOLUME.

area of the grid to yield the grid-square emission rate. The user will make this computation for each grid square needed in the dispersion computations.

E. Dispersion Modeling

1. Dispersion of Pathway Emissions

The consideration of the dispersion of pathway emissions in the manual model will differ somewhat from that in the numerical model. As in the numerical model, a distinction will be made between dispersion on long, limited-access roadways, non-limited-access roadways, and street canyons. However, concentrations will be computed in the manual model through the use of charts and nomographs.

a. Long, Limited-Access Roadways

Long, limited-access roadway segments are those segments on which the emission density is both uniform and continuous for a minimum length of road. For the purposes of commuter exposure modeling, the minimum length is a function of atmospheric stability and wind/roadway angle. Table 10 lists minimum roadway lengths. The user will follow the dispersion computation procedure described in this subsection for all limited-access segments longer than the appropriate minimum length value in Table 10. If the segment is shorter than the minimum length, the procedure described in the next subsection should be followed.

If a roadway segment meets the minimum length criteria, the concentration on the segment, normalized by wind speed, U, and emission rate, Q, can be determined from a set of curves such as those in Figure 31. The normalized concentration is read on the ordinate from the curve corresponding to the appropriate stability and initial dispersion, and for the wind/roadway angle of the segment. When the normalized concentration is multiplied by the emission rate and divided by the wind speed, the result is the concentration at a point on the roadway. To compute the exposure on the segment, one multiplies the concentration by the segment travel time.

b. Non-Limited-Access Roadways

For roadway segments that do not meet the criteria for long, limited-access roadways, and that also are not street canyons, a dispersion methodology for finite line sources will be used. Figure 32 illustrates the geometry of the finite line source. The concept of a reference plane is introduced in this dispersion treatment. The reference plane is marked

TABLE 10

MINIMUM ROADWAY LENGTH
OF AN "INFINITE" LINE SOURCE

		Wind/Roadway Angle (deg)							
Stability Class	σ_{zo} (m)	0	9	18	27	41	53	71	90
D	1.5	>3920	1040	320	160	120	120	100	100
E	1.5	>3920	560	200	140	120	100	100	100
F	1.5	>3920	320	160	120	120	100	100	100
D	5.0	>3920	560	200	140	120	100	100	100
E	5.0	>3920	560	200	140	120	100	100	100

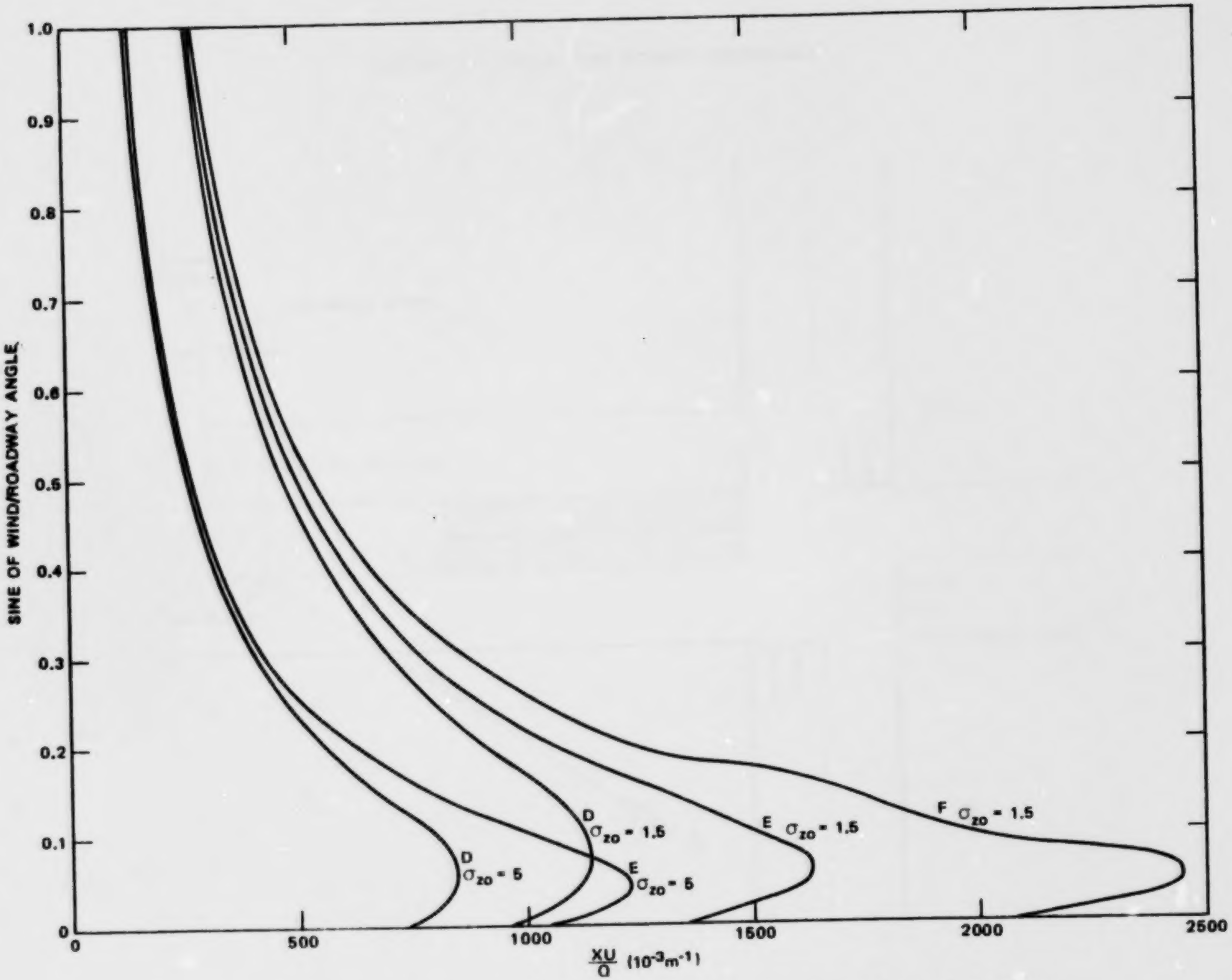

FIGURE 31. NORMALIZED ON-ROADWAY CONCENTRATION VERSUS WIND/ROADWAY ANGLE FOR VARIOUS STABILITIES AND σ_{zo} VALUES FOR AN INFINITE LINE SOURCE

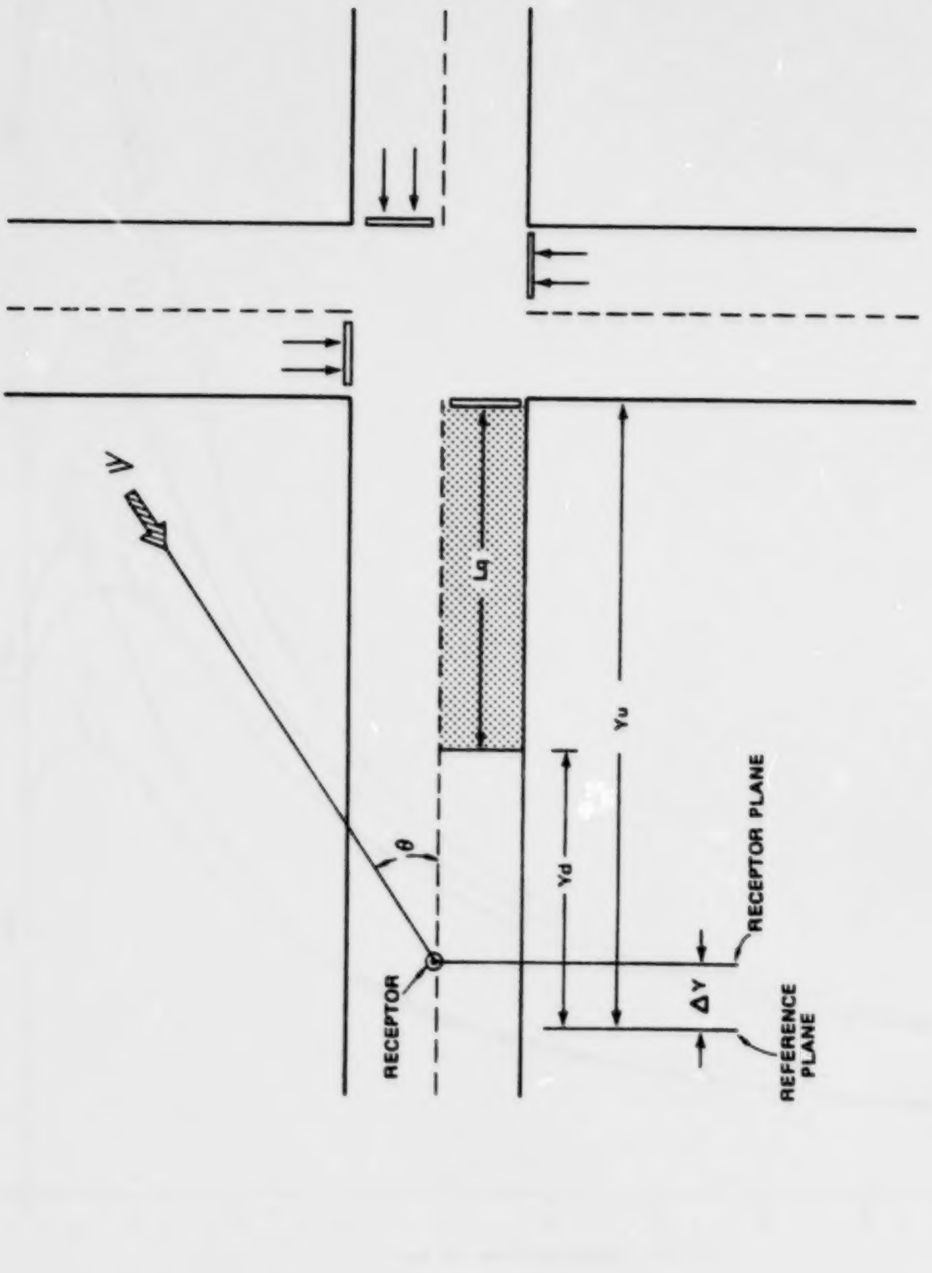
V
θ
RECEPTOR
Lq
Yu
Yd
ΔY
RECEPTOR PLANE
REFERENCE PLANE

FIGURE 32. FINITE LINE SOURCE GEOMETRY

by a line perpendicular to the roadway and located 20 m downwind of the receptor plane. The term Yu denotes the upwind distance along the roadway axis from the reference plane to the upwind edge of the queue; Yu is set equal to zero if the upwind end of the queue is downwind of the reference plane. The term Yd is the upwind distance (measured along the roadway axis) from the reference plane to the downwind end of the queue. It is also set equal to zero if the downwind end of the queue is downwind of the reference plane.

The HIWAY dispersion model[21] was used to generate a series of nomograms that depict the dependence of the normalized concentration on variations in wind/roadway angle and the length (Yu) of the finite line source measured from the reference plane to the upwind edge of the line source. Figure 33 illustrates these curves for specified combinations of stability and σ_{zo}.

For finite line sources, the concentration from the local roadway source can be considered as the sum of two components: (1) the finite line source as represented by the excess emission rate, emitted over the finite length of the queue (Lq); and (2) an infinite line source representative of the nonstopping vehicles passing through. Accordingly, a dual analysis is required -- one for each component. The excess emissions component is found by: (1) obtaining the normalized concentration for the "maximum queue" from Figure 33 using the distance Yu; (2) obtaining the normalized concentration for the "imaginary queue" from Figure 33 using the distance Yd; (3) subtracting the result of (2) from the result of (1); and (4) multiplying the difference by the excess emissions rate and dividing by the wind speed.

Once the two components of the pathway concentration (finite and infinite) are found and summed, the pathway segment exposure can be computed. The exposure is equal to the concentration multiplied by the travel time along the segment.

The procedure described in this subsection requires the user to select a receptor location on the segment. The receptor should be located such that the concentration computed for that location is an

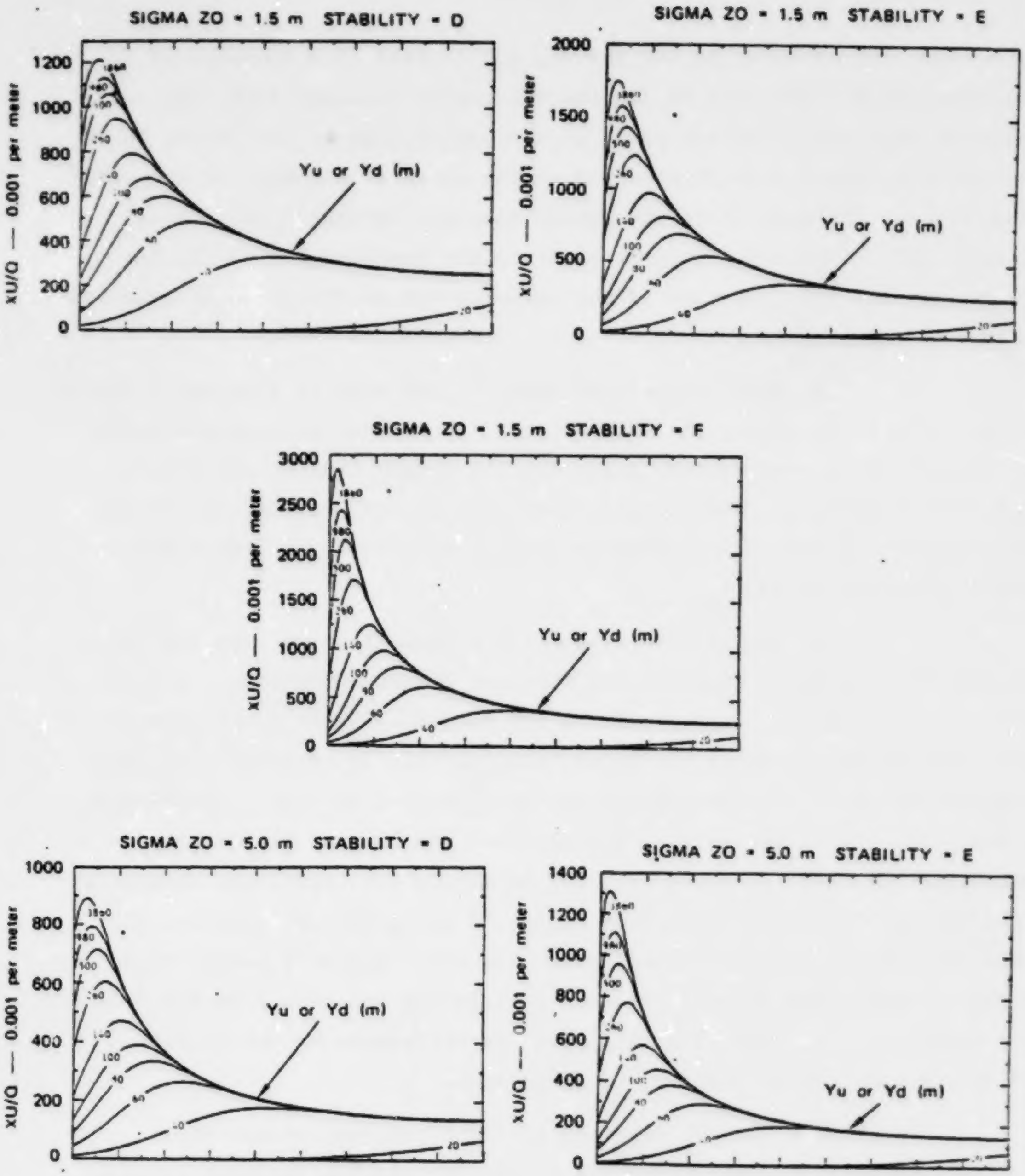

FIGURE 33

VARIATION OF THE NORMALIZED CO CONCENTRATION WITH ROADWAY LENGTH, STABILITY, WIND/ROAD ANGLE, AND TERRAIN ROUGHNESS "average" for the segment. The instructions for the manual commuter exposure model should include nomograms to aid the user in choosing the receptor location. The nomograms would be produced by making a large number of computer computations for various roadway and queue lengths, stabilities, wind/roadway angles, and values of σ_{zo}, and charting the results.

c. Street Canyons

The manual model will use the same technique for computing exposures in street canyons as was used in the short-term mode of the numerical model, only the computation will be done by hand. See the discussion of street canyon dispersion in the numerical model section of this report.

2. Dispersion of Non-Pathway Source Emissions

The dispersion of non-pathway source emissions will be calculated with the same methodology as described for the numerical model, operating in the short-term mode. The concentrations at each of the three points shown in Figure 14 will be hand-calculated and weighted for travel time, as discussed previously. Once those points have been located, it is easy to identify the grid squares (in which the points lie) for which input data will be needed.

F. Summary of Manual Methodology

The first step in the application of the manual model is to select the pathway or pathways to be analyzed. Next, the pollutant source data must be prepared for both pathway and non-pathway sources. For pathways, information on volume and other aspects of traffic is gathered for each segment. To quantify non-pathway emissions, a grid system that overlays the pathway is defined, and the non-pathway vehicle miles traveled in some of the grids through which the pathway passes are tabulated.

Each segment of a pathway will be treated individually. For freeway, expressway, and non-CBD arterial segments of pathways, average route speed will be found and used to compute a FTP emission rate on the segment; travel time will also be computed. On CBD arterials, the effects of signalization and congestion will be accounted for, and modal emissions, as well as travel time, will be found from nomographs.

The normalized concentration on each segment resulting from pathway sources will be computed using different dispersion methodologies, according to whether the segment is a street canyon; limited-access; or non-limited-access, non-street canyon. The exposures on the segment is found by multiplying the concentration by the travel time on the segment.

To determine the pathway exposure resulting from non-pathway sources, the VMT in each grid square is converted to an emission rate through the use of FTP emission factors. The user then computes a concentration at three points on each segment, and weights the concentrations by the travel times between points to compute an exposure for the segment.

The exposure on a pathway is found by summing the pathway and non-pathway source exposures for all segments of the pathway. If more than one pathway is considered with the manual methodology, the user may develop commuter exposure statistics for the worst-case commute.

IV DATA SPECIFICATION

Three topics pertaining to data are discussed in the data specification section of this report. First, the input data required to use both the numerical and manual commuter exposure models are defined. Secondly, the data required for model evaluation are delineated, and finally, the availability of data bases is discussed.

A. Input Data

1. Numerical Model

The types of data that will be required for execution of the numerical commuter exposure model are listed and described in Table 11. The table also contains information on preferred units, data value limits, and typical values.

The data will be entered on eight types of cards. Type 1 contains general information about the computer simulation to be run, such as a heading, the date, and various run flags. The next two card types contain traffic information about each commute pathway segment. One of each of these card types will be input for each segment of each pathway. Card types 4 and 5 contain information required for emissions computations. Information on non-pathway sources will be input on card type 6 (one card for each grid source), and meteorological data will appear on card type 7. Card type 8 contains several output flags which will cause additional output of the specific types requested to be printed.

In Table 11 card types 5 and 7 are shown with two formats. The user will select the format appropriate to the specified mode of model operation (annual or short-term).

Table 11

INPUT DATA REQUIREMENTS FOR THE NUMERICAL COMMUTER EXPOSURE MODEL

Card	Units	Value Limits	Typical Value	Definition
1	--	-	-	Card type number
	--	20 alphanumeric characters	St. Louis Run 1	Heading (anything user wants printed at the beginning of the output)
	--	770101-901231	781215	Date (year, month, day)
	people	> 0	750000	City size
	--	1, 2	1	Model mode of operation; 1=annual, 2=short-term
	--	1, 2	1	Non-pathway emissions; 1=model-calculated, 2=user-supplied

Table 11 (continued)

Card	Units	Value Limits	Typical Value	Description
2	--	-	-	Card type number
	--	1-25	5	Pathway number
	--	≤ 100	17	Segment or link number (one segment or link implies one direction of travel)
	--	1, 2, 3	2	Segment type; 1=limited-access, 2=non-limited-access, 3=street canyon
	veh/hr	≥ 0	3600	Demand volume
	--	-1 or +1	-1	Volume data format; +1=per lane, -1=entire link
	--	-1, 0, +1	+1	Volume data format; -1=ADT, 0=hourly data, +1=AADT
	veh/hr	≥ 0	1800	Lane capacity of segment
	--	1-6	2	Number of lanes on segment
	feet	9-14	12	Lane width
	mi/hr	≥ 0	45	Speed on segment
	map units	> 0	1550.	x-coordinate of first endpoint of segment
	map units	> 0	1430.	y-coordinate of first endpoint of segment
	map units	> 0	1550.	x-coordinate of second endpoint of segment
	map units	> 0	1690.	y-coordinate of second endpoint of segment
	mi/map unit	> 0	1.	Converts map units to miles
	--	0, 1, 2, 3	0	Intersection data; 0=no intersection; 1=toll booth, 2=signalized, 3=freeway backup
	--	1, 2	2	Intersection data; 1=user supplied, 2=model calculated

Table 11 (continued)

Card	Units	Value Limits	Typical Value	Description
3	-	-	-	Card type number
	veh/hr of green	≥ 0	1200	Capacity of segment (or controlling) approach for phase 1 - left turns
	veh/hr of green	≥ 0	1800 per lane	Capacity of segment approach for phase 2 -- through and right turns
	veh/hr of green	≥ 0	1200	Capacity of opposing controlling approach for phase 3 -- left turns
	veh/hr of green	≥ 0	1800 per lane	Capacity of opposing controlling approach for phase 4 -- through and right turns
	veh/hr	≥ 0	600	Demand volume on segment (or controlling) approach for phase 1 -- left turns
	veh/hr	≥ 0	1200 per lane	Demand volume on segment approach for phase 2 -- through and right turns
	veh/hr	≥ 0	600	Demand volume on opposing controlling approach for phase 3 -- left turns
	veh/hr	≥ 0	1200 per lane	Demand volume on opposing controlling approach for phase 4 -- through and right turns
	sec	≥ sum of all phases	90	Cycle length
	sec	≥ 0	15	Phase 1 green time (left turn from segment)
	sec	≥ 0	45	Phase 2 green time (through and right turn from segment)
	veh/hr	≥ 0	600	Segment left turn approach volume
	veh/hr	≥ 0	1200 per lane	Segment through and right turn approach volume
	veh/hr	≥ 0	2300 per lane	Demand volume during backup
	sec	≥ 0	900	Averaging-time

Table 11 (continued)

Card	Units	Value Limits	Typical Value	Description
4	--	--	--	Card type number
	--	0. - 1.0	0.12	Fraction of annual travel driven by vehicles of model year i, i=1, 20
	--	0. - 1.0	0.76	Fraction of annual travel driven by vehicles of type j, j=1, 4
5*	--	--	--	Card type number
	--	0-100	20	Percentage of cold-starting vehicles, evening commute
	--	0-100	30	Percentage of hot-starting vehicles, evening commute
	°F	0-110	50	Annual average air temperature during morning commute
	°F	0-110	60	Annual average air temperature during evening commute
	--	> 0	30	Percentage of average daily VMT during morning commute
	--	> 0	32	Percentage of average daily VMT during evening commute
	--	> 0	2	Average number of occupants in vehicle
5**	--	--	--	Card type number
	--	0-100	20	Percentage of cold-starting vehicles for commute of interest
	--	0-100	30	Percentage of hot-starting vehicles for commute of interest
	°F	0-110	73	Average air temperature during commute of interest
	hr	> 0	2	Duration of commute of interest
	--	> 0	16	Percentage of daily VMT during hour i of the commute; i = 1, end of commute
	--	> 0	2	Average number of occupants in vehicle

*For annual mode of operation

**For short-term mode of operation

Table 11 (continued)

Card	Units	Value Limits	Typical Value	Description
6	--	--	--	Card type number
	map units	> 0	1525.	x-coordinate of SW corner of gird square
	map units	> 0	1310.	y-coordinate of SW corner of grid square
	veh-mi/day	> 0		VMT in grid square
	--	1, 2, 3, 4, 5	1	Grid square locale type; 1=CBD, 2=commercial/suburban, 3=residential, 4=industrial, 5=rural/other
	g/hr	$\geq 0.$	4500.	Grid square average daily emission rate
7^{*}	--	--	--	Card type number
	--	0. - 1.0	0.002	Joint frequency of occurrence of stability k, wind direction ℓ, wind speed m; k = 1,6; ℓ = 1,16; m = 1,6
7^{**}	--	--	--	Card type number
	m/sec^{-1}	$\geq 0.$	2.4	Wind speed during hour i of commute; i = 1, end of commute
	degrees	0-360	120	Wind direction during hour i of commute; i = 1, end of commute
	--	1-6	4	Stability during hour i of commute; i = 1, end of commute

[*] For annual mode of operation

[**] For short-term mode of operation

Table 11 (concluded)

Card	Units	Value Limits	Typical Value	Description
8***	--	--	--	Card type number
	--	1 to no. of pathways	1, 8, 17	Up to 5 pathway numbers for which percentage of commuters in each of several exposure classes will be printed
	--	1 to no. of pathways	2, 10, 21	Up to 5 pathway numbers for which probability of experiencing exposure levels in each of several exposure classes will be printed
	--	1 to no. ofpathways	10	Pathway number for which exposures for the meteorological conditions given below will be printed
	--	1-576	62, [illegible], 342, 461	Up to 10 numbers of sets of meteorological conditions for which exposure on pathway above will be printed (see Table 12)
	--	0, 1	1	Flag for graphics package; 0 = no graphical output, 1 = call graphical package

***Optional output may be generated with this card

a. Card Type 1

The data to be entered on the card type 1 are general in nature. First is an alphanumeric heading, which may be up to 20 characters long. The heading may say anything the user would like to have printed at the beginning of model output. Next, the data and size of the city being modeled will be input. Finally, two flags will be set, specifying the desired mode of operation for the model (annual or short-term) and whether non-pathway emissions are to be entered directly or calculated by the model.

b. Card Type 2

Some of the data on card types 2 and 3 are direct traffic engineering parameters, and some are flags that are operationally important to running the model. The inputs describing the traffic volume data format are in the latter category.

The data listed for card type 2 will be needed for analysis of uninterrupted traffic flow. The user must identify the pathway and segment by number, and provide data on the demand volume, number of lines, lane capacity, lane width, and the endpoint coordination of the segment. Flags are available to convert demand volume given as ADT or AADT to hourly values. Capacity may be entered directly if known, or a default input of 2,000 veh/hr will cause capacity to be calculated from lane width, percent trucks (input elsewhere), and number of lanes data. Similarly, speed may be entered if known, but a zero value will cause speed to be calculated from the capacity restraint relationships. The endpoint coordinate of the segment may be entered in any convenient, consistent units and then converted to miles by a conversion factor specified by the user.

At the end of card type 2 are two flags concerning data on intersections. The first describes the existence and type of intersection (including interrupted flow on expressways); the second is a flag that denotes whether or not the user is supplying the intersection data.

c. Card Type 3

Card type 3 will supply the intersection data. When the user supplies these data, the model skips to the cycle-length input and reads the remaining data. Left-turn, and through and right-turn signal phases are allowed by the model.

To calculate the signal parameters, inputs will be required for each of the three phases for the two critical approaches to the interesection. (Those are the approaches with the highest volume-to-capacity ratios from north-south and east-west directions). The inputs will be the capacity service volume (vehicles per hour of green) and the demand volume for each phase on each approach. Approaches without a separate left-turn phase are considered through entering a zero for the corresponding capacity service volume.

If the model is to calculate the signal parameters, the cycle length and green phase times should not be entered. However, the segment approach volumes must still be entered to accommodate the rare case when the segment is not a critical approach.

The final inputs on card type 3 need be entered when back-ups on expressways occur (when a flag value of 3 is entered as the next-to-last entry on card type 2). The required data will be the demand volume and the time during which demand exceeds capacity. During the remainder of the one-hour period, the demand volume from card type 2 will be used.

d. Card Type 4

The distributions of model year and vehicle type needed to compute mobile source emissions are entered on card type 4. The fraction of the annual travel by each of 20 model years, beginning with the calendar year being modeled and followed by the 19 previous model years, is entered on this card. Finally, the fractions of the annual travel driven by light-duty vehicles, light-duty trucks, heavy-duty gasoline-powered trucks, and heavy-duty diesel trucks will be input.

e. Card Type 5

The type of data to be entered on card type 5 depends on the mode of operation of the model. A description of the data required for both the annual and short-term modes of operation is given in Table 11.

For the annual mode, the model will require the entry of the annual average percentage of cold-starting and hot-starting vehicles for the evening commute. Commuting vehicles usually begin the evening commute in the CBD; therefore, the percentage should refer to the CBD. The annual average temperatures for the morning and evening commute periods will be entered next. Those temperatures, along with the percentage of cold-starting and hot-starting vehicles, will be used by the model in computing emission factors. The next data entered on card type 5 (annual mode) will be the percentages of the average daily VMT during the morning and evening commutes. Those values will be used in the computation of non-pathway source emissions.

For the short-term mode of operation, the input data on card type 5 are similar to those for the annual mode, but the data are for only one commute. The percentages of cold-starting and hot-starting vehicles refer to the commute time of interest. The percentages should apply to the locale in which most of the commute vehicles begin their trips. The temperature entered on card type 5 should be an average temperature during the commute being analyzed. Next, the number of hours the commute lasts should be entered, and then the percentage of the average daily VMT during each hour of the commute should be input.

For either mode of model operation, the average number of occupants for all vehicle types should be input.

f. Card Type 6

Data describing the grid squares will be entered on card type 6. One card should be input for each grid square through which a pathway passes. The first data to appear on card type 6 are the coordinates of the southwest corner of the grid square. The next entry will depend on whether the model is to compute non-pathway source emissions or whether emissions are to be input directly. If the model is to compute non-pathway source emissions, the next input will be the average daily VMT in the grid square, followed by the locale type associated with the grid square. If emissions are to be input directly, the average daily emission rate for the square should be entered in lieu of the grid square VMT and locale type.

g. Card Type 7

The meteorological data are entered into the model on card type 7. As with card type 5, different formats and data will be used for the two different modes of model operation.

For the annual mode, the joint frequency distribution of wind direction, wind speed, and atmospheric stability should be entered. The distributions consist of the fraction of the time that each combination of wind direction, speed, and stability occur. There are 16 wind direction classes, 6 wind speed classes, and 6 stability classes.

For the short-term mode, values for wind speed, wind direction, and stability should be entered for each hour of the commute of interest. The number of values of each of those parameters that is entered should correspond to the duration of the commute as it appears on card type 5.

h. Card Type 8

Card type 8 is an optional data card. If the model user elects to utilize one or more of the optional output features of the commuter exposure model, card type 8 should be included. If only some of the options available are to be used, zeroes should be entered for all remaining inputs on the card.

The first set of input values on card type 8 will consist of the numbers of those pathways for which the user wants the percentage of commuters on each of the pathways in each of several exposure classes to be printed. The output can be obtained for up to five pathways.

The next set of input values will contain the numbers of those pathways for which the user wants the probability of the commuters on each of the pathways experiencing exposure levels in each of several exposure classes to be printed. As many as five pathway numbers can be input.

The next values to be entered on card type 8 will allow the user to observe the variation of exposure on a specific pathway with meteorological conditions. First, the number of the pathway of interest will be entered. Next, the number associated with a particular combination of wind direction class, wind speed class, and atmospheric stability class will be entered. The model will allow up to 10 sets of meteorological conditions to be input. The number associated with each combination of meteorological conditions will be taken from Table 12. The definitions of the value intervals for the wind direction, wind speed, and stability referred to in Table 12 appear in Table 13.

The final input on the card will be a flag for the graphics package. If the flag is set to a value of one, a graphics package will be called that will plot the "pollution roses" discussed in Section II-F-3.

Table 12

NUMBERS ASSOCIATED WITH EACH COMBINATION OF WIND SPEED CLASS, WIND DIRECTION CLASS, AND STABILITY CLASS

STABILITY 1							STABILITY 2							STABILITY 3						
WIND DIRECTION CLASS	WIND SPEED CLASS						WIND DIRECTION CLASS	WIND SPEED CLASS						WIND DIRECTION CLASS	WIND SPEED CLASS					
	1	2	3	4	5	6		1	2	3	4	5	6		1	2	3	4	5	6
1	1	2	3	4	5	6	1	97	98	99	100	101	102	1	193	194	195	196	197	198
2	7	8	9	10	11	12	2	103	104	105	106	107	108	2	199	200	201	202	203	204
3	13	14	15	16	17	18	3	109	110	111	112	113	114	3	205	206	207	208	209	210
4	19	20	21	22	23	24	4	115	116	117	118	119	120	4	211	212	213	214	215	216
5	25	26	27	28	29	30	5	121	122	123	124	125	126	5	217	218	219	220	221	222
6	31	32	33	34	35	36	6	127	128	129	130	131	132	6	223	224	225	226	227	228
7	37	38	39	40	41	42	7	133	134	135	136	137	138	7	229	230	231	232	233	234
8	43	44	45	46	47	48	8	139	140	141	142	143	144	8	235	236	237	238	239	240
9	49	50	51	52	53	54	9	145	146	147	148	149	150	9	241	242	243	244	245	246
10	55	56	57	58	59	60	10	151	152	153	154	155	156	10	247	248	249	250	251	252
11	61	62	63	64	65	66	11	157	158	159	160	161	162	11	253	254	255	256	257	258
12	67	68	69	70	71	72	12	163	164	165	166	167	168	12	259	260	261	262	263	264
13	73	74	75	76	77	78	13	169	170	171	172	173	174	13	265	266	267	268	269	270
14	79	80	81	82	83	84	14	175	176	177	178	179	180	14	271	272	273	274	275	276
15	85	86	87	88	89	90	15	181	182	183	184	185	186	15	277	278	279	280	281	282
16	91	92	93	94	95	96	16	187	188	189	190	191	192	16	283	284	285	286	287	288

Table 12 (concluded)

STABILITY 4							STABILITY 5							STABILITY 6						
WIND DIRECTION CLASS	WIND SPEED CLASS						WIND DIRECTION CLASS	WIND SPEED CLASS						WIND DIRECTION CLASS	WIND SPEED CLASS					
	1	2	3	4	5	6		1	2	3	4	5	6		1	2	3	4	5	6
1	289	290	291	292	293	294	1	385	386	387	388	389	390	1	481	482	483	484	485	486
2	295	296	297	298	299	300	2	391	392	393	394	395	396	2	487	488	489	490	491	492
3	301	302	303	304	305	306	3	397	398	399	400	401	402	3	493	494	495	496	497	498
4	307	308	309	310	311	312	4	403	404	405	406	407	408	4	499	500	501	502	503	504
5	313	314	315	316	317	318	5	409	410	411	412	413	414	5	505	506	507	508	509	510
6	319	320	321	322	323	324	6	415	416	417	418	419	420	6	511	512	513	514	515	516
7	325	326	327	328	329	330	7	421	422	423	424	425	426	7	517	518	519	520	521	522
8	331	332	333	334	335	336	8	427	428	429	430	431	432	8	523	524	525	526	527	528
9	337	338	339	340	341	342	9	433	434	435	436	437	438	9	529	530	531	532	533	534
10	343	344	345	346	347	348	10	439	440	441	442	443	444	10	535	536	537	538	539	540
11	349	350	351	352	353	354	11	445	446	447	448	449	450	11	541	542	543	544	545	546
12	355	356	357	358	359	360	12	451	452	453	454	455	456	12	547	548	549	550	551	552
13	361	362	363	364	365	366	13	457	458	459	460	461	462	13	553	554	555	556	557	558
14	367	368	369	370	371	372	14	463	464	465	466	467	468	14	559	560	561	562	563	564
15	373	374	375	376	377	378	15	469	470	471	472	473	474	15	565	566	567	568	569	570
16	379	380	381	382	383	384	16	475	476	477	478	479	480	16	571	572	573	574	575	576

Table 13

DEFINITION OF VALUE INTERVALS OF WIND DIRECTION, WIND SPEED, AND STABILITY CLASSES

WIND DIRECTION CLASS	WIND DIRECTION INTERVAL (DEGREES)	WIND SPEED CLASS	SPEED INTERVAL (KNOTS)	STABILITY CLASS	DEFINITION
1	11.25 - 33.75	1	0-3	1	Very Unstable
2	33.75 - 56.25	2	4-6	2	Moderately Unstable
3	56.25 - 78.75	3	7-10	3	Slightly Unstable
4	78.75 -101.25	4	11-16	4	Neutral
5	101.25 -123.75	5	17-21	5	Slightly Stable
6	123.75 -146.25	6	>21	6	Stable
7	146.25 -168.75				
8	168.75 -191.25				
9	191.25 -213.75				
10	213.75 -236.25				
11	236.25 -258.75				
12	258.75 -281.25				
13	281.25 -303.75				
14	303.75 -326.25				
15	326.25 -348.75				
16	348.75 - 11.25				

2. Manual Model

The types of data that will be required for execution of the manual model are listed in Table 14. Many other data elements will be required, but they will appear on the worksheets or will be taken by the user from the tables, nomograms, etc. in the User's Guide for the manual model.

The requirements for traffic data for the manual model are essentially the same as for the numerical model except that the various flags are not needed. Table 14 lists the necessary data. (The data are described in the previous discussion of inputs for the numerical model.)

Emission data will be taken by the user from the appropriate figures in the User's Guide. The meteorological parameters that will be required by the model are also listed in Table 14, and were described in the previous discussion of numerical model inputs.

Table 14

DATA REQUIREMENTS FOR THE MANUAL COMMUTER EXPOSURE MODEL

Description	Units	Value Limits	Typical Value
For each pathway segment:			
Pathway number	-	>1	5
Segment or link number (one direction of travel)	-	>1	17
Demand volume	veh/hr	≥0	3600
Lane capacity of segment	veh/hr	>0	1800
Number of lanes on segment	-	1-6	2
Lane width	ft	9-14	12
Speed on segment	mi/hr	>0	45
Segment length	mi	>0	1
Capacity of segment (or controlling) approach for phase 1 - left turns	veh/hr of green	≥0	1200
Capacity of segment (or controlling) approach for phase 2 - through and right turns	veh/hr of green	≥0	1800 per lane
Capacity of opposing controlling approach for phase 3 - left turns	veh/hr of green	≥0	1200
Capacity of opposing controlling approach for phase 4 - through and right turns	veh/hr of green	≥0	1800 per lane
Demand volume on segment (or controlling) approach for phase 1	veh/hr	≥0	600
Demand volume on segment (or controlling) approach for phase 2	veh/hr	≥0	1200 per lane

Table 14 (continued)

Description	Units	Value Limits	Typical Value
Demand volume on opposing controlling approach for phase 3	veh/hr	≥ 0	600
Demand volume on opposing controlling approach for phase 4	veh/hr	≥ 0	1200 per lane
Cycle length	sec	$\geq$ sum of all phases	90
Phase 1 green time	sec	≥ 0	15
Phase 2 green time	sec	≥ 0	45
Segment left turn approach volume	veh/hr	≥ 0	600
Segment through and right turn approach volume	veh/hr	≥ 0	1200 per lane
Demand volume during backup	veh/hr	≥ 0	2300 per lane
Averaging time for backup	sec	≥ 0	900
For each grid square:			
VMT in grid square	veh-mi/day	>0	
Grid square locale type; 1 = CBD, 2 = commercial/suburban, 3 = residential, 4 = industrial, 5 = rural/other	-	1,2,3,4,5	1
Remaining data required:			
Average temperature of the commute	°F	0-110	60
Percentage of average daily VMT during commute	-	>0	30
Average number of commuters in vehicle	-	>2	2

Table 14 (concluded)

Description	Units	Value Limits	Typical Value
Wind speed during commute	m $\sec^{-1}$	$\geq 0.$	2.4
Wind direction during commute	degrees	0-360	120
Stability during commute	-	1-6	4
City size	people	>0	750,000

B. Data Required for Evaluation of the Model

The commuter exposure model outlined in this report can be evaluated in more than one way. One method of evaluation is to determine the adequacy of the simulation in terms of the reliability of the results. To evaluate the overall model from an air pollution standpoint, data describing the model ouput, commuter exposure (time-integrated concentration), is needed. Ideally, such data would be obtained by having a statistically significant sample of commuters carry a personal monitor that could time-integrate the concentration to which the commuter is exposed. The readings from the personal monitors could be compared with model calculations to arrive at a quantitative measure of overall model performance.

Another way of evaluating model performance, and one through which insight into model inadequacies could be gained, is to individually evaluate the major modules of which the model is comprised. One method of evaluating individual modules is to compare the output of each major module with empirically derived data. The three major modules that should be analyzed individually are the modules that treat traffic, emissions, and dispersion. The following paragraphs contain a discussion of the data requirements of an evaluation of each of these modules.

For evaluation of the output of the traffic module, the following parameters are needed. For pathway segments that have uninterrupted and uncongested flow, the average route speed on the segment will be required to evaluate the output of the traffic module. For pathway segments on which flow is uninterrupted but congested, the length and duration of the backup will be needed, in addition to the average route speed. For pathway segments that have interrupted flow, the cruise speed, queue length, signal cycle parameters, average delay time, and rates of acceleration and deceleration are required.

The performance of the emissions module in simulating roadway emissions is difficult to test empirically. In the commuter exposure model, the currently-accepted EPA methodologies are used to compute emissions. It is assumed that these methodologies represent the state of the art in emissions simulation.

The output of the dispersion module is the pollutant concentration on each pathway segment. A single concentration is computed for each pathway segment and, when multiplied by the travel time on the segment, is assumed to represent the time-integrated concentration for the segment. To evaluate the output, two questions must be asked: (1) Does the single concentration computed for the segment correspond to the actual average concentration on the segment? (2) Is the variation of concentration along the segment such that an integration of the measured concentrations can be represented by the product of the travel time on the segment and the computed "average" concentration? Such an analysis requires measurement of on-roadway concentration at frequent intervals on each pathway.

The evaluation of the dispersion module discussed above would indeed be an analysis of the performance of the dispersion module alone if the inputs to the dispersion module accurately represented the emissions and meteorological conditions on the pathway segment. However, the emission rate used by the dispersion module is obtained from the emission module. Because an evaluation of the emissions module output would require an effort considered beyond the scope of a typical model evaluation study, for carbon monoxide the dispersion module must be evaluated in conjuntion with the emissions module.

This problem can be eliminated, however, if the measurements recommended for use in the evaluation of the dispersion module could be made for a tracer gas released at a known rate from a test vehicle. The known emission rate would be entered into the dispersion module, along with site-specific meteorological parameters. The output of the dispersion module then could be tested against measured concentrations of the tracer gas to determine the reliability of the dispersion modeling procedure.

One other part of the model that should be evaluated is an assumption made in the commuter exposure modeling methodology, specifically, that on-roadway and in-vehicle concentrations of carbon monoxide are equivalent. This theory is based on limited studies and is used in lieu of any evidence to the contrary. An evaluation of the commuter exposure model should include further investigation of the relationship between concentrations of carbon monoxide on the roadway and inside the vehicle. Simultaneous measurements should be made inside and outside various vehicle types, models, and makes, under different conditions, such as with windows up and down, the air conditioner on and off, vents open and closed, and smoking being or not being practiced inside the vehicle.

C. Data Base Availability

The commuter exposure modeling methodologies were designed so that the input data required would be routinely available from federal, state, and local agencies. The numerical model will be most applicable to major metropolitan areas, with the exception that the New York and Los Angeles areas would require special procedures due to their size and complexity. In general, the larger is the urban area to be modeled, the more detailed are the available data.

The traffic information required on card types 2, 3 and 5 in Table 11 is generally available from the state department of transportation or the local transit district. Instructions on how to define the commute pathways from various types of data appear in Section II-B-1 of this report. Section II-B-2 contains a discussion of how the grid system should be defined and how the traffic input for card type 6 should be obtained.

Perhaps the weakest data are those that concern the commute pathways of individual or even small traffic groups of commuters. These data are simply not available. The best that can be done is to deal with commuters in the aggregate, and to work with major commuting routes that are used by a majority of commuters for a majority of their trips, at least in terms of exposure.

The distributions of vehicle model year and vehicle type required on card type 4 may be available for the local modeling area from the traffic agencies. If these data are not available, the model will have the national average distributions in storage, and those distributions may be used as default variables.

The percentages of cold-starting and hot-starting vehicles required on card type 5 should be determined according to the method described by Midurski, et al.[22] The meteorological data called for on card types 5 and 7 can be obtained from the National Climatic Center (NCC) in Asheville, N.C. If the model is to be run in the annual mode, the joint frequency distribution can be produced by the NCC STAR program from a historical meteorological record for any first-order weather station.

The data required for model evaluation are described in the preceding section. In general, most of these data are not available. The authors of this report know of only one study[17] in which personal monitors were carried, and in that study, data were not taken outside the vehicle in which the commuter was riding.

The data required to evaluate the individual modules of the model do not exist. However, measurements in the automobiles of a few commuters over a number of commutes (and commute paths) could be made with a relatively modest effort. While such measurements would not be ideal for discerning the accuracy of the individual modules of the model, they would provide an indication of overall model performance. Concurrent traffic count and signal data would provide more confidence in the study results.

Some indication of model performance can be gained through use of existing data. Where local monitors are already in place near commuting routes, their data would provide a reference for model calculations. In that case, the accuracy of the dispersion models in predicting on-roadway concentrations, and the relationship between on-roadway and in-vehicle concentrations, would still be questionable.

V CRITICAL EVALUATION OF MODELING APPROACHES

Following is a critical evaluation of the modeling approaches presented in Sections II and III of this report. The costs of developing each of the models are detailed, and the deficiencies and accuracies of the methodologies are discussed.

A. Development Costs

To detail the costs of developing the commuter exposure models, a breakdown of the tasks to be accomplished should be presented. The following list shows the tasks in developing the numerical model:

1. Formulate the structure of the numerical commuter exposure model code.
2. Design a User's Guide that will describe the model and its operation.
3. Write the computer code of the numerical model.
4. Write the User's Guide.
5. Produce monthly, interim, and final reports that fully describe the model development.

The cost of accomplishing these tasks in the development of the numerical model is estimated at approximately 2,300 person-hours and $83,000. This cost includes labor and direct costs, such as computer time, materials and supplies, communications, travel, and report costs. The labor costs were estimated according to SRI's currently approved overhead rates.

Development of the manual model would consist of the following tasks:

1. Formulate the structure of a manual commuter exposure model.
2. Develop the tables, worksheets, nomograms, and so forth, needed to use the model.

(3) Write a User's Guide that describes and illustrates application of the manual model.

The cost of accomplishing these tasks, in conjunction with or following the development of the numerical model, is estimated at 1,000 person-hours and $33,000.

B. Model Deficiencies

In most instances the commuter exposure model uses state-of-the-art technology to simulate the traffic, vehicle emissions, and pollutant dispersion affecting commuters in an urban area. The areas in which improvements are needed to state-of-the-art techniques are well known and have been widely discussed. For example, the use of a Gaussian distribution to represent the variation in pollutant concentration usually assumes a steady-state condition for periods of up to one-hour in duration. Of course, wind direction and speed and many other descriptive parameters can vary considerably during such a time period. Thus, the assumption of a steady-state is not always valid and ideally should be replaced by a treatment that can accommodate high frequency variations in basic descriptive parameters. Deficiencies of this sort are well known, and as the state of the art progresses, they will be eliminated.

The model deficiencies discussed here are those relating to assumptions made in formulating the methodology that, while not ideal, were necessary to produce a practical, useful model of a reasonable size and moderate running costs. To keep the modeling problem tractable, certain assumptions were necessary. In designing the methodology, care was taken that such assumptions would have a relatively minor effect on the model output.

Table 15 contains a list of model deficiencies. First, and most important, is that the model does not treat all commuters. Short commutes and commutes on less popular routes are not treated. While ideally all commuters would be treated, the number of origin-destination zone pairs in a major metropolitan area needed to define all commute routes is far greater than can be reasonably handled. Another possible model deficiency is the method by which commute routes are defined. The method is only semi-objective. If the model user is familiar with the areas to be modeled and is experienced in traffic modeling, he will undoubtedly make better choices of commute routes than would a less experienced person. The suggestion that the local transportation agency be contacted for help in selecting the commuting routes mitigates this somewhat.

To keep the calculation of annual average exposures within reasonable computational bounds, no peaks (other than diurnal) are allowed in the traffic distribution. If the volume input to the model is annual average daily traffic (AADT), the lack of peaking characteristics will not be a problem. However, if average daily traffic (ADT) is input, the lack of weekly and seasonal peaks could affect the annual average exposures. This effect can be alleviated by adjusting ADT to AADT using seasonal factors when computing annual average exposures. Another model assumption is that the acceleration and deceleration rates have a constant value, although the effects of this are expected to be minor. Single, constant rates may be chosen that reflect the average emissions from a distribution of rates.

Three assumptions are made relating to the computation of emission rates. The assumptions are necessary to keep the number of model computations and the computer storage required at realistic levels. First, an annual average ambient air temperature is used where the model is in the annual mode. Next, in the morning all vehicles on the commute routes are assumed to be in a warmed-up mode of operation. (The vehicles reached this state while traveling to the beginning of the commute route.) Finally, when computing pollutant concentrations resulting from non-pathway sources, fixed cold-start and hot-start percentages are assumed for the morning and evening commutes for each locale type.

Four possible model deficiencies are related to the simulation of atmospheric dispersion. The use of the Gaussian dispersion formulations presented precludes treatment of fumigation or stagnation conditions.

Table 15

MODEL DEFICIENCIES

Not all commuters are treated

Semi-objective method of commute pathway selection

No seasonal or weekly traffic distribution

Constant acceleration and deceleration rates

Assume annual average ambient air temperature

All morning commute vehicles assumed hot-running

Cold-start and hot-start percentages fixed for each locale type for morning and evening commutes

Gaussian dispersion treatments cannot treat fumigation or stagnation

Non-pathway dispersion treatment does not allow variation of grid square emission rates

No provision for effects of precipitation

On-roadway and in-vehicle concentrations assumed equal

The Hanna-Gifford dispersion treatment used to compute concentrations resulting from non-pathway sources assumes that the emission rate in grid squares adjacent to the receptor square is the same as the emission rate in the receptor grid square. Another factor which has been ignored in the commuter exposure modeling methodology is the effect of precipitation. Undoubtedly some scavenging or rainout would occur. Finally, on-roadway and in-vehicle concentrations have been assumed to be equal. The state of the windows, air conditioner, heater, and so forth in the vehicle would affect this relationship.

C. Model Accuracies

A number of equations are presented or derived for the traffic module of the commuter exposure model. These relate "independent" traffic parameters to other, dependent parameters. The dependent or predicted parameters are in turn used in the emission calculations, and the output of the emissions module is then used in dispersion computations. A method is presented below that investigates the relative accuracies or relative errors of the predicted traffic variables as functions of the relative errors of the independent traffic variables. A discussion of the accuracy of the emissions and dispersion modules of the model is presented at the end of this subsection.

1. Method for Determining Relative Error

Define the relative error of a variable , x, as

$$E_x = \frac{S_x}{\bar{x}}$$

where E_x is the relative error, S_x is the standard deviation of x, and $\bar{x}$ is the mean of x. In stating that the value of x is 5 ± 10%, the 10% is the relative error expressed as a percent.

In general, if $z = f(x_1, x_2, \ldots, x_n)$, then

$$S_z^2 = \sum_{i,j=1}^{n} \left(\frac{\partial z}{\partial x_i}\right)_p \left(\frac{\partial z}{\partial x_j}\right)_p S_{x_j x_i} \qquad \text{(C)}$$

where p is the point at which the derivatives are evaluated, assumed to be the mean or observed value. Note that $S_{x_i x_i} = S_{x_i}^2$. Assuming that the errors are independent yields

$$S_{x_i x_j} = 0, \; i \neq j.$$

If $z = xy$ then

$$S_z^{\,2} = (\bar{y})^2 \, S_x^{\,2} + (\bar{x})^2 \, S_y^{\,2}.$$

Dividing by $\bar{z}^2$ and taking the square root gives

$$\frac{S_z}{\bar{z}} = \sqrt{{\frac{S_x}{\bar{x}}}^2 + {\frac{S_y}{\bar{y}}}^2}$$

or

$$E_z = \sqrt{E_x^{\,2} + E_y^{\,2}} \tag{D}$$

The same relation holds for division.

For $z = x + y$ or $z = x - y$,

$$S_z = S_x^{\,2} + S_y^{\,2}$$

Dividing by $\bar{z}$,

$$\frac{S_z}{\bar{z}} = \sqrt{\frac{S_x^{\,2}}{\bar{z}^2} + \frac{S_y^{\,2}}{\bar{z}^2}} \quad \text{, or}$$

$$\frac{S_z}{\bar{z}} = \sqrt{\frac{S_x^{\,2}}{\bar{x}^2}\,\frac{\bar{x}^2}{\bar{z}^2} + \frac{S_y^{\,2}}{\bar{y}^2}\,\frac{\bar{y}^2}{\bar{z}^2}} \quad \text{, and}$$

$$E_z = \sqrt{E_x^{\,2}\left(\frac{\bar{x}}{\bar{z}}\right)^2 + E_y^{\,2}\left(\frac{\bar{y}}{\bar{z}}\right)^2} \tag{E}$$

Finally, note the assumption that $\bar{z} = f(\bar{x}_1, \bar{x}_2, \ldots, \bar{x}_n)$. While this is not, in general, a strict equality, it provides a best estimate of $\bar{z}$.

The sensitivity of the relative error in z to a change in the relative error in the other variables can be easily evaluated. Taking

$$E_z = \sqrt{A^2E_x{}^2 + B^2E_y{}^2} \quad ,$$

where $A = \bar{x}/\bar{z}$ or 1

and $B = \bar{y}/\bar{z}$ or 1,

then

$$\frac{\partial E_z}{\partial E_x} = \frac{A^2E_x}{E_z}$$

and

$$\frac{\partial E_z}{\partial E_y} = \frac{B^2E_y}{E_z}$$

In general,

$$\frac{\partial E_z}{\partial E_{x_i}} = \frac{K^2E_{x_i}}{E_z} \qquad \text{(F)}$$

where K is the relative weighting as defined above.

2. Application of the Method to Traffic Parameters

Six basic equations were introduced for the traffic module to predict queue lengths and delay times.
These are

Queue length of a freeway backup

$$\hat{N} = \frac{(q-s)t'}{1-q'/s} \qquad \text{(G)}$$

Associated delay

$$D = \frac{kN^2}{v\hat{N}} \tag{H}$$

Queue length at a signalized intersection

$$N = \frac{1-G/Cy}{1-V/Cs} \quad \frac{V\ Cy}{3600} \tag{I}$$

Associated delay

$$D = 0.5(Cy-G) \tag{J}$$

Queue length at a toll booth

$$N = \frac{V}{C-V} \tag{K}$$

Associated delay

$$D = \frac{3600\ N}{C} \tag{L}$$

The equations for the propagation of errors and the sensitivities of the resultant errors are derived below for the freeway backup case. Relationships for the other two cases are not presented but are derived similarly.

a. Example - Freeway Backup Case

Given

$$\hat{N} = \frac{(q-s)t'}{1-q'/s}$$

$$= \frac{sqt'-s^2t'}{s-q'}$$

then

$$S_N^{\,2} = \left(\frac{\partial\hat{N}}{\partial q}\right)^2 S_q^{\,2} + \left(\frac{\partial\hat{N}}{\partial s}\right)^2 S_s^{\,2} + \left(\frac{\partial\hat{N}}{\partial t'}\right)^2 S_{t'}^{\,2} + \left(\frac{\partial\hat{N}}{\partial_{q'}}\right)^2 S_{q'}^{\,2}$$

$$= \left(\frac{st'}{s-q'}\right)^2 S_q^{\,2} + \left[\frac{(s-q')(qt'-2st') - sqt' + s^2t'}{(s-q')^2}\right]^2 S_s^{\,2}$$

$$+ \left(\frac{sq-s^2}{s-q'}\right)^2 S_{t'}^{\,2} + \left[\frac{sqt'-s^2t'}{(s-q')^2}\right]^2 S_{q'}^{\,2}$$

Dividing by $\hat{N}^2$ and reducing, this becomes

$$E_{\hat{N}} = \left\{\left(\frac{st'q}{s-q'}\right)^2 \left(\frac{E_q}{\hat{N}}\right)^2 + \left(\frac{s}{\hat{N}}\right)^2 \left[\frac{2q'st'-s^2t'-qq't'}{(s-q')^2}\right]^2 E_s^{\,2}\right.$$

$$\left. + E_{t'}^{\,2} + \left[\frac{sqt'-s^2t'}{(s-q')^2}\right]^2 \frac{q'}{\hat{N}}^2 E_{q'}^{\,2}\right\}^{1/2}$$

The sensitivity of this relative error in N to changes in the relative errors in the independent variables can be calculated using equation (F):

$$\frac{\partial E_{\hat{N}}}{\partial E_q} = \left(\frac{st'q}{s-q'}\right)^2 \frac{1}{\hat{N}^2} \frac{E_q}{E_{\hat{N}}}$$

$$\frac{\partial E_{\hat{N}}}{\partial E_s} = \left(\frac{s}{\hat{N}}\right)^2 \left[\frac{2q'st'-s^2t'-qq't'}{(s-q')^2}\right]^2 \frac{E_s}{E_{\hat{N}}}$$

$$\frac{\partial E_{\hat{N}}}{\partial E_{t'}} = \frac{E_{t'}}{E_{\hat{N}}}$$

$$\frac{\partial E_N}{\partial E_{q'}} = \left[\frac{sqt'-s^2t'}{(s-q')^2}\right]^2 \left(\frac{q'}{\hat{N}}\right)^2 \frac{E_{q'}}{E_{\hat{N}}}$$

The relative error and sensitivity relationships for equations (H) through (L) are derived in the same manner.

3. Results of Sample Applications

The results of applying the relative error and sensitivity relationships derived for equations (G) through (L) are presented in Tables 16, 17, and 18. The specific numerical results should be interpreted with caution, since they depend on the values and relative errors assigned to the independent variables. However, doubling the relative error in all of the independent variables doubles the relative error of the predicted values. The sensitivities will remain unchanged. Such statements cannot be made when the values and relative errors of the independent variables are varied at random. The numerical results are quite useful, however, for examining the general propagation of errors and the sensitivities of the predictive equations.

From Table 16, the relative error in the prediction of the number of vehicles involved in the freeway backup is 117%, while the relative error in the delay prediction is 85%. The error in predicting N is most sensitive to the error in s, the roadway capacity, and next most sensitive to q, the over-capacity demand volume. This is encouraging, since the roadway capacity is the parameter that can most likely be estimated with the least error. Reducing the relative error in this parameter from 10% to 5% would improve the relative error in N by 33% in this example. The relative error in the delay prediction, E_D, is most sensitive to the relative error in the over-capacity demand volume. This unfortunate result implies that the relative error in D is difficult to improve because it is so highly sensitive to a transient condition.

Turning to Table 17, the relative error in the queue length prediction is 42%, and the relative error is 36% for the associated delay. Again, both depend on the conditions assumed for the example. Both

Table 16

RELATIVE ERROR AND SENSITIVITIES FOR THE FREEWAY BACKUP CASE

$$\hat{N} = \frac{(q-s)t'}{1-q'/s}$$

$q = 0.64$ veh/sec

$s = 0.55$ veh/sec

$q' = 0.40$ veh/sec

$t' = 1800$ sec

$h = 1.8$ sec

$\hat{N} = 594$ veh

$E_{\hat{N}} = 1.17$

$= 117\%$

$$\frac{\partial E_{\hat{N}}}{\partial E_q} = 4.34$$

$$\frac{\partial E_{\hat{N}}}{\partial E_s} = 6.61$$

$$\frac{\partial E_{\hat{N}}}{\partial E_{q'}} = 0.61$$

$$\frac{\partial E_{\hat{N}}}{\partial E_{t'}} = 0.09$$

$$D = \frac{ht'\ (q-s)(s-q')}{s}$$

$E_q = 10\%$

$E_s = 10\%$

$E_{q'} = 10\%$

$E_{t'} = 10\%$

$E_h = 10\%$

$D = 79.5$ sec

$E_D = 0.85$

$= 85\%$

$$\frac{\partial E_D}{\partial E_q} = 5.96$$

$$\frac{\partial E_D}{\partial E_s} = 1.40$$

$$\frac{\partial E_D}{\partial E_{q'}} = 0.84$$

$$\frac{\partial E_D}{\partial E_{t'}} = 0.12$$

$$\frac{\partial E_D}{\partial E_h} = 0.12$$

Table 17

RELATIVE ERROR AND SENSITIVITIES FOR THE SIGNALIZED INTERSECTION CASE

$$N = \frac{1-G/Cy}{1-V/Cs} \quad \frac{V\ Cy}{3600}$$

$G = 60$ sec

$Cy = 90$ sec

$V = 600$ veh/hr

$Cs = 1200$ veh/hr

$N = 10$ veh/cycle

$E_N = 0.42$

$= 42\%$

$$\frac{\partial E_N}{\partial E_G} = 0.94$$

$$\frac{\partial E_N}{\partial E_{Cy}} = 2.12$$

$$\frac{\partial E_N}{\partial E_V} = 0.94$$

$$\frac{\partial E_N}{\partial E_{Cs}} = 0.24$$

$$D = 0.5\ (Cy-G)$$

$E_G = 10\%$

$E_{Cy} = 10\%$

$E_V = 10\%$

$E_{Cs} = 10\%$

$D = 15$ sec/veh

$E_D = 0.36$

$= 36\%$

$$\frac{\partial E_D}{\partial E_G} = 1.11$$

$$\frac{\partial E_D}{\partial E_{Cy}} = 2.50$$

Table 18

RELATIVE ERROR AND SENSITIVITIES FOR THE TOLL BOOTH CASE

$N = \frac{V}{C-V}$

$V = 400$ veh/hr

$C = 1200$ veh/hr

$N = 0.5$ veh

$E_N = 0.21$

$= 21\%$

$\frac{\partial E_N}{\partial E_V} = 1.06$

$\frac{\partial E_N}{\partial E_C} = 1.06$

$D = \frac{3600V}{C(C-V)}$

$E_V = 10\%$

$E_C = 10\%$

$D = 1.5$ sec

$E_D = 0.29$

$= 29\%$

$\frac{\partial E_D}{\partial E_V} = 0.77$

$\frac{\partial E_D}{\partial E_C} = 2.14$

relative errors are most sensitive to the relative error in the cycle length, the parameter that generally can be known with least error. Improving the relative error in the cycle length from 10% to 5% leads to E_N of 31% and E_D of 24%.

Table 18 lists the results for the case of a toll booth. E_N is equally sensitive to the relative errors in volume and capacity with a nearly one-to-one relationship. E_D, on the other hand, is more sensitive to E_c and less sensitive to E_v than is E_N.

Finally, the dependence of all of these results on the absolute values assumed for the dependent variables should be reemphasized. The results are not absolute but rather indicate general dependencies, and they must be interpreted accordingly. For any specific case, an exact investigation of relative error and sensitivity requires calculations using the values of the parameters for that case. This can be accomplished easily using equations (C) through (F) to find the proper relationships and then applying these with the specific parameter values.

4. Accuracies of Emissions and Dispersion Algorithms

The emission module will take the average route speed computed by the traffic module, and use speed, ambient air temperature, the percentages of cold-starting and hot-starting vehicles, and the vehicle type and age distributions to compute emission rates. Error in any of these parameters will produce error in the computed emission rate. The magnitude of the relative error is difficult to determine. The method presented in the preceding sections could be applied to the emission rate equation. However, the complexity of the emissions equation is such that the resulting equation representing relative error would be ungainly. An assessment of the accuracy of the emissions estimation procedure employed in the commuter exposure model can be made more readily by relying on EPA estimates of the accuracy of their procedure.

In assessing the accuracies of the dispersion algorithms the same problem that was encountered in examining the accuracy of the emissions module appears: the complexity of the algorithms. However, there is one parameter, the source emission rate, that is directly proportional to segment concentration. Therefore, a given error in emission rate will produce the same amount of error in concentration.

The effects of error in other parameters are in some cases considerably more subtle. For example, the model accepts atmospheric stability expressed as a Pasquill-Gifford class. The dispersion algorithms do not use the class number directly, however; the number determines the values of constants used in the computation of the horizontal and vertical dispersion coefficients. Another such input parameter is wind direction. The direction from which the wind is blowing is used by the model to determine the x- and y- distances from source to receptor in a coordinate system with the origin at the source and the x-axis along the direction of the wind. The x- and/or y- distances appear in the relationships for σ_x and σ_y as well as in exponential terms of both components of the concentration equations.

As stated above, several of the parameters that govern concentration are not used directly, and the expressions for non-street canyon concentrations are very complex. Since the equations used for non-street canyon segments in the commuter model are based on the assumption that concentration follows a Gaussian distribution, and the standard Gaussian dispersion equations have been widely investigated, the results of such investigations can be useful here. In general, the overall Gaussian dispersion formulation has been shown in validation studies to predict concentration within a factor of two of measured concentrations. Since the commuter exposure model utilizes a Gaussian formulation, it can be expected to predict exposure with a commensurate degree of accuracy.

The empirically-derived equation used to represent on-roadway concentrations in street canyons contains only three dependent variables; the equation is simple enough to apply the method presented in Subsection V-C-1.

The equation for concentration, X, is

$$X = \frac{KQ_\ell}{2(U+0.5)} \left[\frac{1}{L_o} + \frac{1}{W}\right]$$

To simplify application of the method, the assumption is made that the street width, W, is considerably larger than the dimension representing vehicle size, L_o. The above equation then reduces to

$$X = \frac{KQ_\ell}{2L_o(U+0.5)}$$

Applying equation (C),

$$S_X{}^2 = \left(\frac{\partial X}{\partial Q_\ell}\right)^2 S_{Q_\ell}{}^2 + \left(\frac{\partial X}{\partial U}\right)^2 S_U{}^2$$

$$= \left[\frac{K}{2L_o(U+0.5)}\right]^2 S_{Q_\ell}^2 + \left[\frac{-KQ_\ell}{2L_o(U+0.5)^2}\right]^2 S_U{}^2$$

Dividing by X^2 and reducing,

$$E_X = \left\{E_{Q_\ell}^2 + \left[\frac{U}{(U+0.5)}\right]^2 E_U{}^2\right\}^{1/2}$$

Table 19 contains the results of applying the relative error and sensitivity relationships for a given set of variable values. The results shown in Table 19 are intended as an illustration of the method and should not be interpreted as general in nature.

Table 19

RELATIVE ERROR AND SENSITIVITIES FOR STREET CANYON CONCENTRATION

$$X = \frac{KQ_{\ell}}{2L_o(U+0.5)}$$

$L_o = 2$ m

$U = 4$m/sec

$K = 7$

$Q_{\ell} = .1$ g/sec

$X = 38.9\mu g/m^3$

$E_X = 0.13 = 13\%$

$E_{Q_{\ell}} = 0.10 = 10\%$

$E_U = 0.10 = 10\%$

$$\frac{\partial E_X}{\partial E_{Q_{\ell}}} = \frac{E_{Q_{\ell}}}{E_X}$$

$$\frac{\partial E_X}{\partial E_U} = \left[\frac{U}{(U+0.5)}\right]^2 \frac{E_U}{E_X}$$

$$\frac{\partial E_X}{\partial E_{Q_{\ell}}} = 0.75$$

$$\frac{\partial E_X}{\partial E_U} = 0.61$$

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